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# NAVAL POSTGRADUATE SCHOOL

## MONTEREY, CALIFORNIA

**STRUCTURAL DESIGN OF A NPS CUBESAT LAUNCHER**

by

Felix Roßberg

January 2008

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Prepared for: Space Systems Academic Group

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**13. ABSTRACT (maximum 200 words)**


To encourage student interest in space and education, Stanford University and CalPoly developed the CubeSat. These picosatellites weigh about one kg and can be developed and built by students. NPS is designing CubeSats and a structure to deploy them in orbit as part of its emphasis on hands-on education

This technical report deals with the development of a CubeSat Launcher (NPSCuL). NPSCuL will carry up to ten P-PODs, built and flight qualified by CalPoly. It will be launched into orbit and deploy multiple CubeSats. Several designs have been developed, including finite element models, each with a variable number of elements and shell wall thicknesses and tested to loads of 15 g. The simulation results show that the aluminum structures need to have a minimum shell thickness of 15 mm to handle the maximum expected stress. Different bolt patterns for the connection between the structure and the base plate were analyzed. A circular bolt pattern is preferred because the stress is distributed more evenly over the bolts, but the shell thickness was modified based on the results from the frequency analysis.


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To encourage student interest in space and education, Stanford University and CalPoly developed the CubeSat. These picosatellites weigh about 1 kg and can be developed and built by students. NPS is designing CubeSats and a structure to deploy them in orbit as part of its emphasis on hands-on education

This technical report deals with the development of a CubeSat Launcher (NPSCuL). NPSCuL will carry up to ten P-PODs, built and flight qualified by CalPoly. It will be launched into orbit and deploy multiple CubeSats. Several designs have been developed, including finite element models, each with a variable number of elements and shell wall thicknesses and tested to loads of 15g. The simulation results show that the aluminum structures need to have a minimum shell thickness of 15 mm to handle the maximum expected stress. Different bolt patterns for the connection between the structure and the base plate were analyzed. A circular bolt pattern is preferred because the stress is distributed more evenly over the bolts, but the shell thickness was modified based on the results from the frequency analysis.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| CAE | Computer Aided Engineering |
| CalPoly | California Polytechnic State University |
| CG | Center of Gravity |
| COTS | Commercial off-the-shelf-electronics |
| DoD | Department of Defense |
| EELV | Evolved Expendable Launch Vehicle |
| ESPA | EELV Secondary Payload Adapter |
| FE | Finite Element |
| NASA | National Aeronautics and Space Administration |
| NPS | Naval Postgraduate School |
| NPSCuL | Naval Postgraduate School CubeSat Launcher |
| P-POD | Poly Picosat Orbital Deployer |
| SPL | Secondary Payload |
| SSAG | Space Systems Academic Group |
| SSIP | Secondary Standard Interface Plane |
| STP | Space Test Program |

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# I. INTRODUCTION

The Naval Postgraduate School in Monterey is currently designing CubeSats and a structure to deploy them in orbit. The growing popularity of CubeSats for educational and research goals is tempered by the limited launch opportunities to get them into space. To help provide launch opportunities for CubeSat developers to launch their CubeSats, NPS developed the concept of a CubeSat Launcher [1]. This thesis describes the initial work to design structures capable of meeting the needs for a CubeSat launcher.

## A. STRUCTURE OF THIS TECHNICAL REPORT

In Chapter II, the theoretical foundations for the requirements for a secondary payload are given. Additionally, the fundamental ideas of the CubeSats and the P-PODs are presented. This chapter also gives a short overview about working with common Computer Aided Engineering (CAE) tools. The third chapter discusses the different design options for the NPSCuL structure. After mentioning the requirements all options are presented and followed by a comparison. The final structure options were tested to expected stress levels to ensure sufficient capacity while under the acceleration loads caused by the launch vehicle.

Chapter IV is the conclusion and includes suggestions for further research.

## B. OBJECTIVE OF THIS TECHNICAL REPORT

The objective of this thesis is to design a structure that satisfies the requirements for NPSCuL, which must meet ESPA structural requirements. Different design options for NPSCuL will be developed and tested to determine their ability to carry up to ten P-PODs. The different designs will be analyzed to ensure they meet the stress and dynamics requirements. It is expected that there will be design iterations to arrive at the final design.

# II. THEORETICAL FOUNDATIONS

Since early in the 20th century, people have been trying to send objects into orbit. The first people to accomplish this feat were the Russians, putting Sputnik 1 in orbit in 1957, marking the beginning of the satellite era. Fifty years later satellites with different tasks such as communication, reconnaissance, and in-space scientific testing are in use. Miniature satellites have become particularly attractive because smaller and lighter satellites require smaller and cheaper launch vehicles to reach their intended orbits. Depending on the launch vehicle, several of these miniature satellites may be launched together. Furthermore, the development and production should be less expensive which will result in a lower risk in case of a failure before the end of the satellite's mission design life. Another positive aspect is the opportunity to be adapted as a secondary payload by using the excess capacity of a large launch vehicle.

**Table 1: Satellite mass categories [2]**

| Category | Mass range [kg] |
|---|---|
| Large satellite | > 1,000 |
| Medium-sized satellite | 500 – 1,000 |
| Minisatellite | 100 – 500 |
| Microsatellite | 10 – 100 |
| Nanosatellite | 1 – 10 |
| Picosatellite | 0.1 – 1 |
| Femtosatellite | <0.1 |

## A. ESPA REQUIREMENTS

The current generation of launch vehicles can launch satellites with a greater mass than previous generations of launch vehicles. Miniaturized satellites could be launched using excess capacity that the launch vehicle has available by the use of secondary payload adaptors (Figure 2). Therefore, the ESPA interface was designed to carry up to six SPLs. The SPLs are mounted radially and each is deployed at a predetermined time along the primary mission trajectory.

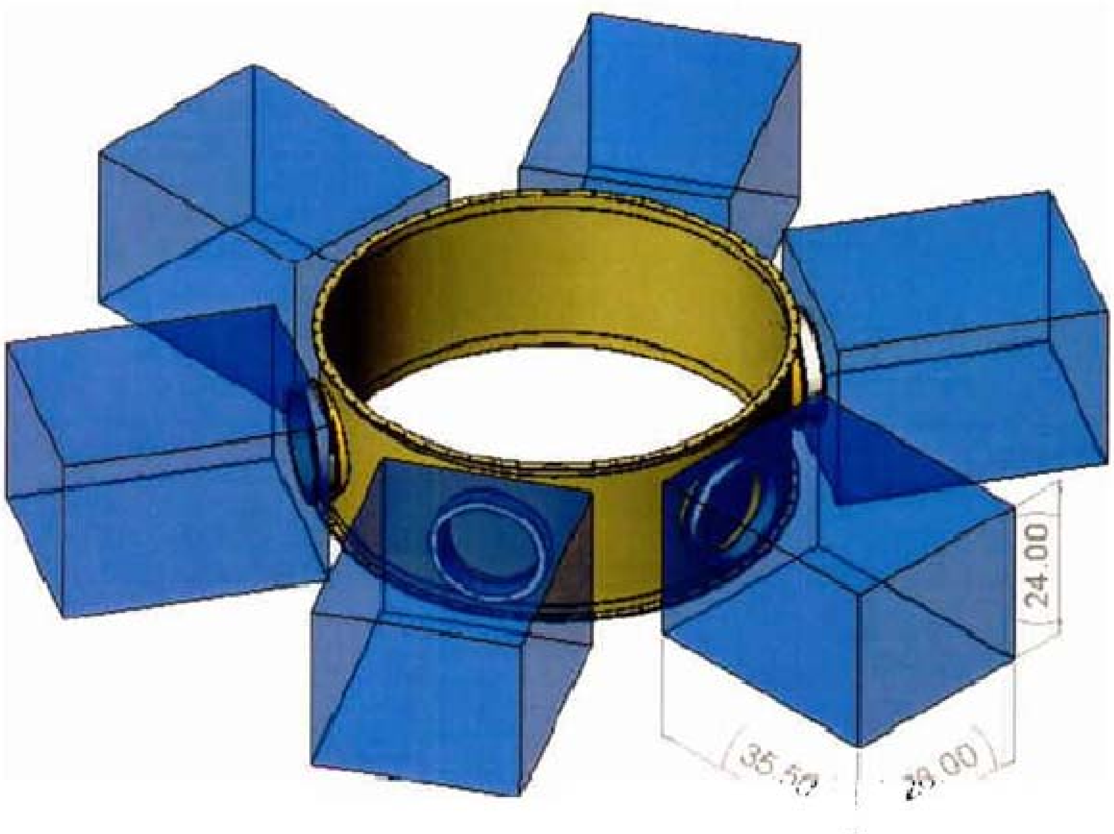


**Figure 1: SPL Envelope Definition [2]**

Figure 1 shows that there is a maximum volume for each secondary payload. According to the requirements, the secondary payload and its separation system must fit into an envelope of 90.1 x 71.1 x 60.9 cm and shall not exceed a mass of 181 kg. Another important issue is the location of the center of gravity (CG). The CG has to be within a 50.8 cm offset of the Secondary Standard Interface Plane (SSIP). Usually the designer of the secondary payload has to fit everything into the required dimension envelope, but to be launched on an ESPA ring the satellite must also possess a mass and CG that assures a balanced ESPA.

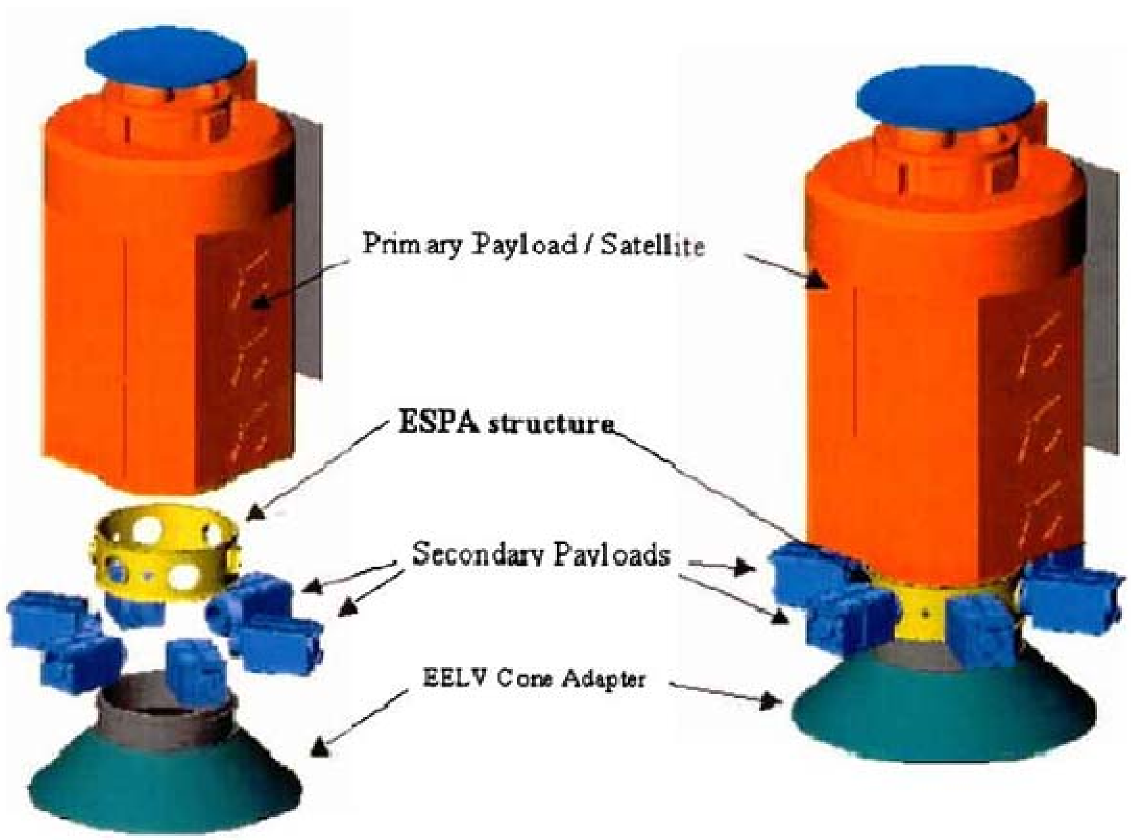


**Figure 2: ESPA stack on EELV [2]**

## B. CUBESAT

Thinking about miniaturizing satellites, Stanford University and CalPoly developed the CubeSat. Figure 3 shows the CubeSat, which is a small cube satellite with the dimensions of 10 x 10 x 10 centimeters and a mass of one kilogram. The standard 1U CubeSat can carry one or two scientific instruments as its primary mission payload. It is also possible to extend it up to a 2U or 3U (30 x 10 x 10 cm), and perhaps a 5U CubeSat (50 x 10 x 10 cm) in the future, to create a more capable satellite. Other options could include a “six-pack”, being developed by NASA Ames and a 2U x 2U x 5U CubeSat (20 x 20 x 50 cm), referred to as a “ten-pack”, being considered by NPS.

**Figure 3: 1U CubeSat**

Most CubeSats use commercial off-the-shelf-electronics to ensure lower satellite developing costs. Using COTS technology, estimated costs for one CubeSat are between US$ 30,000 and US$ 40,000, making it affordable for universities and other educational institutions [3].

Right now, over 60 universities, high schools, and private firms all over the world have developed and are currently developing CubeSats containing private, scientific, and governmental payloads [4]. One idea is to share the knowledge

gained as an international collaboration. Therefore, the users can attend special workshops, where they can share experiences and learn about related topics such as new technologies or the status and availability of potential launch vehicles. Information sharing will be imperative in the reduction of a satellite's development time and potentially its cost. This may allow more student projects to be achieved in a smaller period by using standardized procedures, parts and potentially experiments.

**Figure 4 A-E: Current and possible CubeSat Designs**

**Table 2: CubeSat Specifications**

| Figure | Name | Length (mm) | Mass (kg) |
|---|---|---|---|
| A | 1U | 113.5 | 1 |
| B | 2U | 227 | 2 |
| C | 3U | 340.5 | 3 |
| D | “six-pack” (3Ux2U) | 340.5 | 6 |
| E | 5U | 567.5 | 5 |

## C. POLY PICOSATELLITE ORBITAL DEPLOYER (P-POD)

The P-POD is a standardized deployment structure developed by the California Polytechnic State University (CalPoly) for up to three CubeSats. This is the mechanical and electric interface between the CubeSats and the launch vehicle. It also protects the primary payloads from the CubeSats and vise versa. To satisfy all requirements for launch vehicle providers as well as the CubeSat developers, the design of the P-POD had to account for the following [5]:

- The P-POD must protect the launch vehicle and other payloads from any mechanical, electrical or electromagnetic interference from the CubeSats in the event of a catastrophic CubeSat failure.
- The CubeSats must be released from the P-POD with minimum spin and a low probability of collision with the launch vehicle or other CubeSats.
- The P-POD must have the ability to interface with a variety of launch vehicles with minimum modifications and with no changes to the CubeSat standard.
- The mass of the P-POD should be kept to a minimum.
- The P-POD should incorporate a modular design that allows different numbers of CubeSats to be launched on any given mission.
- The resulting CubeSat standard should be easily manufactured without using exotic materials and expensive construction techniques.

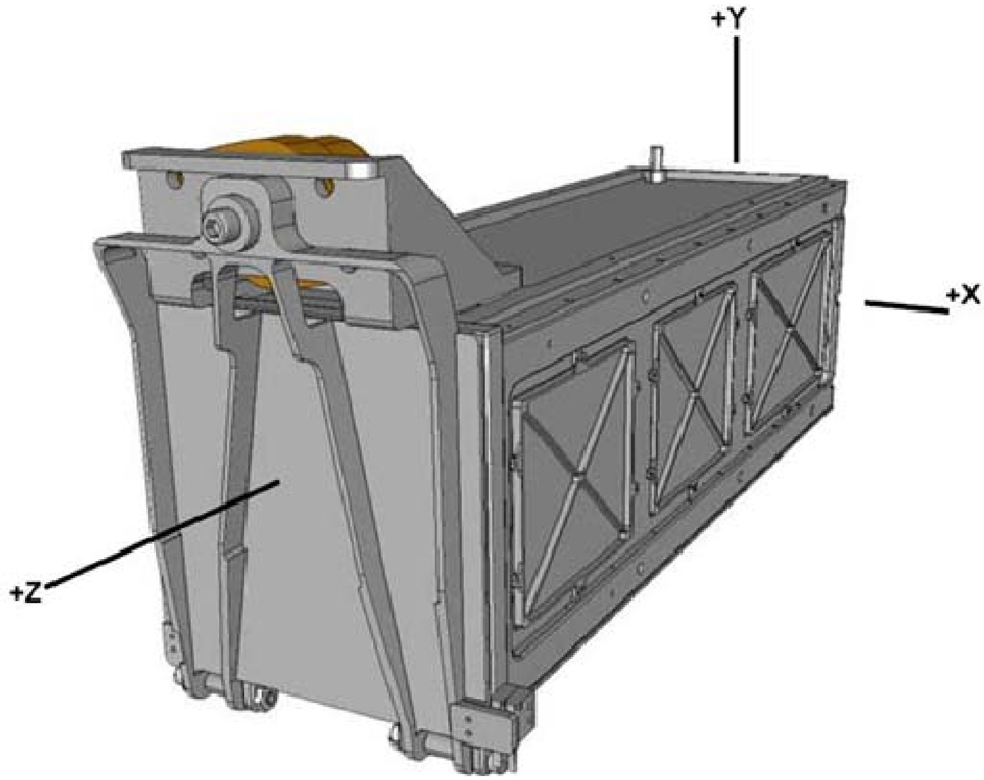


**Figure 5: P-POD Mk III [6]**

In general, the P-POD is a tubular bin built from Aluminum 7075-T73. A movable lid covers the top and mounting holes are situated on every side panel. After receiving the launch signal from the launch vehicle the door will be released by a non-pyrotechnic door opening mechanism. It can be opened up to 270 degree or can be stopped at a certain angle by a user-defined doorstopper. The main spring will push the CubeSats to slide out of the P-POD. To prevent jamming, the interior of the P-POD is processed with a Teflon impregnated hard anodize.

The 3U of CubeSats can be in the form of a single 3U CubeSat, a 2U CubeSat, a 1U CubeSat or some combination thereof. Currently CalPoly is working on an extended P-POD with the capability to deploy a 5U CubeSat as shown in Figure 11.

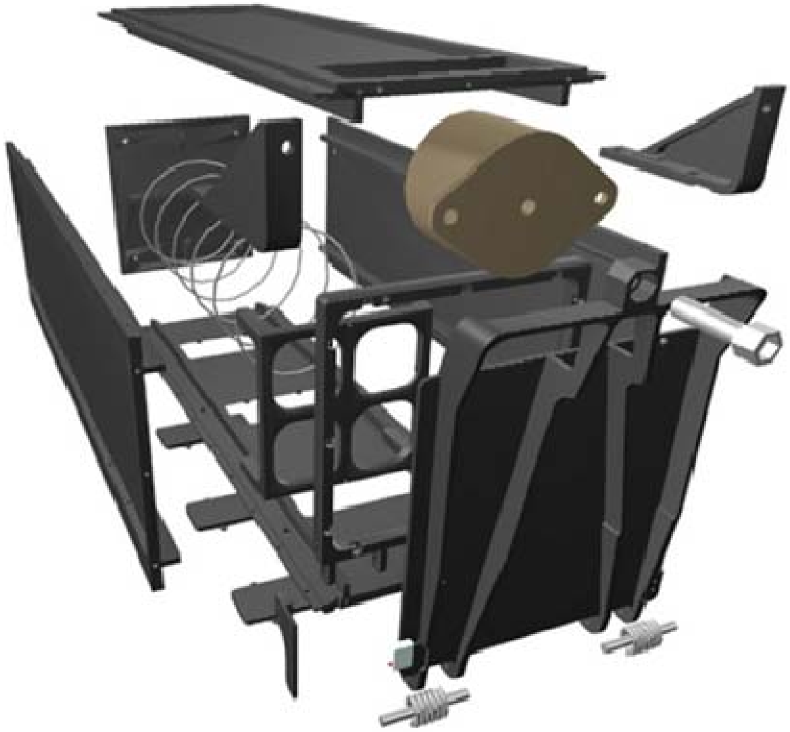

**Figure 6: Expended P-POD [7]**

## D. CAE-TOOLS

Using CAE-tools during the process of developing a certain structure for launch saves money and time before building a prototype. It is very easy to analyze properties like stress, dynamics or thermal effects. As a result of the calculations the geometry can be modified to accomplish the different requirements.

At the beginning of the development process, the geometry of the structure has to be defined. Afterwards the geometrical properties have to be checked and perhaps modified. It is not necessary to consider every small detail, some of them like small holes or radii can be neglected, otherwise they would produce a tiny mesh that would require a long time to solve.

After defining the geometry and the mass properties, it is necessary to mesh the whole structure. In CAE modeling, 1D, 2D, and 3D meshing are

possible and the user has to decide which one applies best for the current structure. In the case under consideration, the 2D mesh is used, because a 1D mesh would be too simple and a 3D mesh would add many more degrees of freedom than required for the structures. The CAE-Tool meshes the structure automatically, the mesh has to be checked afterwards for guilty. To upgrade the accuracy of the solution, three methods are common [8]:

**P-method**: raising the order of the differential equation

**H-method**: defining smaller elements

**HP-method**: combination of the H- and P-method

The Space Systems Academic Group at the NPS is working with the CAE-software UGS I-DEAS 12. This program uses a fixed number of differential equations and that is why the user cannot apply the P-method. Otherwise, the user is defining the geometry and meshing of a part, so the H-method can be used. The only limiting factor of this method is the time required to compute the results, because every node creates six differential equations.

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# III. STRUCTURAL DESIGNS OF THE NPSCUL

## A. REQUIREMENTS

Before starting to design a structure of the NPSCuL, all of the necessary requirements should be known. Generally the ESPA-requirements (II.A) are only the requirements for the external shape. Nevertheless, there are additional requirements, which have to be considered:

- “Hot spare” capability
- Deployable
- 2 by 2 CubeSat
- Mass reconfigurable
- Easy to assemble

As shown in Figure 1, the ESPA ring can carry up to six SPLs. In the event one of the satellites will not be completed before the integration deadline, a slot for another satellite will be open. Therefore, the NPSCuL has to have the capability to be a “hot spare”, which means nothing has to be changed at the structure with the assembled P-PODs, just add the CubeSats. Another requirement is the capability to be deployable. In some cases, the program manager of the primary payload wants every SPL deployed before the launch of the main satellite. Thus, it should be possible to add a separation mechanism like a Lightband. As mentioned in II.B, some CubeSats can be bigger than the usual 1U size. The NPSCuL should also be able to carry bigger P-PODs like a 2U x 2U x 5U. There might be some CubeSats that will carry photo or video systems where lenses of a diameter bigger than 10 cm are used. It should be possible to assemble the required P-PODs using the same structure. The

structure also has to be mass reconfigurable and easy to assemble. If it is necessary to have a certain CG or a certain mass, the structure should have some options to add additional weight.

## B. STRUCTURAL COMPONENTS

The main structural components of the NPSCuL are the baseplate with the Lightband, the structure and the P-PODs.

The baseplate is the circular mechanical interface between the ESPA ring and the structure. It has a bolt pattern with a diameter of 15 inches and consists of 24 – ¼-inch clearance holes that are evenly spaced (15 degrees apart) around the ring.

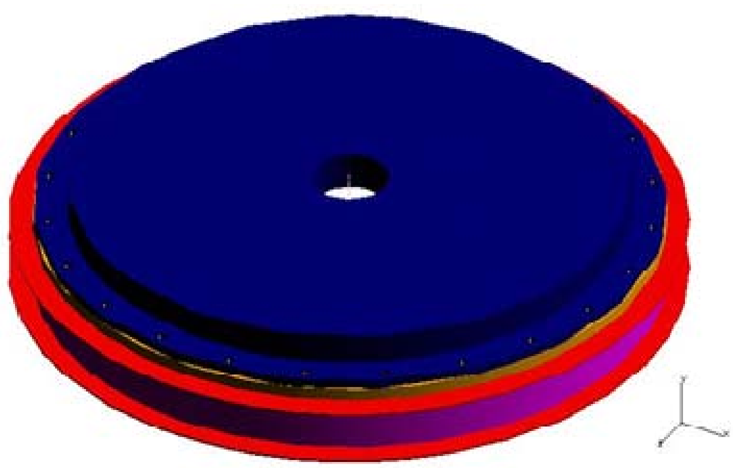

**Figure 7: I-DEAS model of Lightband and baseplate (blue)**

If it is required, a Lightband can be mounted to the baseplate. In the current case, the Mark II Lightband of the Planetary Systems Corporation will be used. This Lightband consist of a lower ring, which is mounted to the ESPA ring and an upper ring, which is mounted to the NPSCuL.

Figure 8: 15 inches Lightband stowed [9]

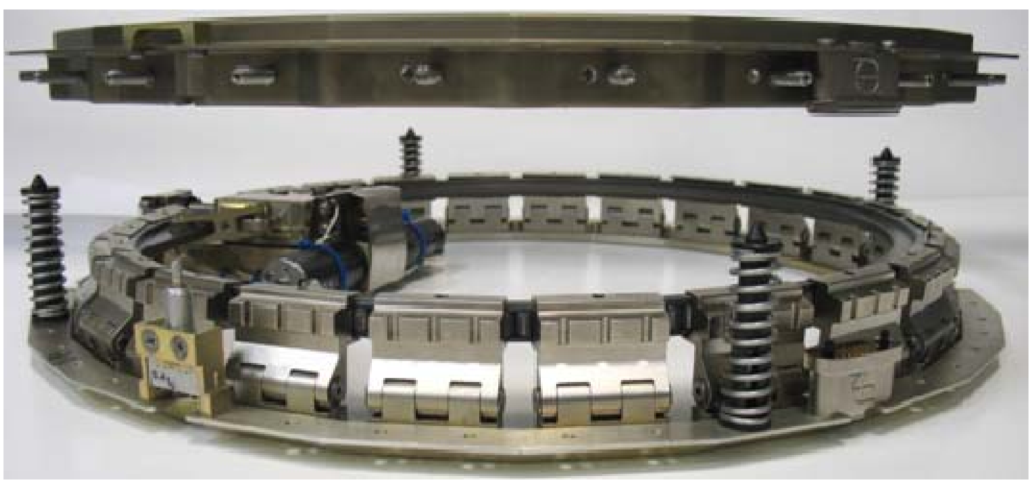

Figure 9: 15 inches Motorized Lightband Deployed [10]

The lower ring carries the separation springs, the hinged leaves, a retaining ring and the motor mechanism. After getting the separation signal, the motor pushes a sliding tube inward. The sliding tube instantly snaps, allowing the compressed retaining ring to contract. Spring plungers help disengage

leaves from the upper ring and separation springs push the two rings apart. This all is done without pyrotechnics so sensitive components are protected from high shock and there is no need for expensive safety features.

The structure of the NPSCuL has to fit into the ESPA required envelope. It also has to be stiff enough to handle an acceleration of 10 g in each direction of the coordinate system at the same time. Figure 10 shows some possible structures. Advantages and disadvantages are discussed in III.C.

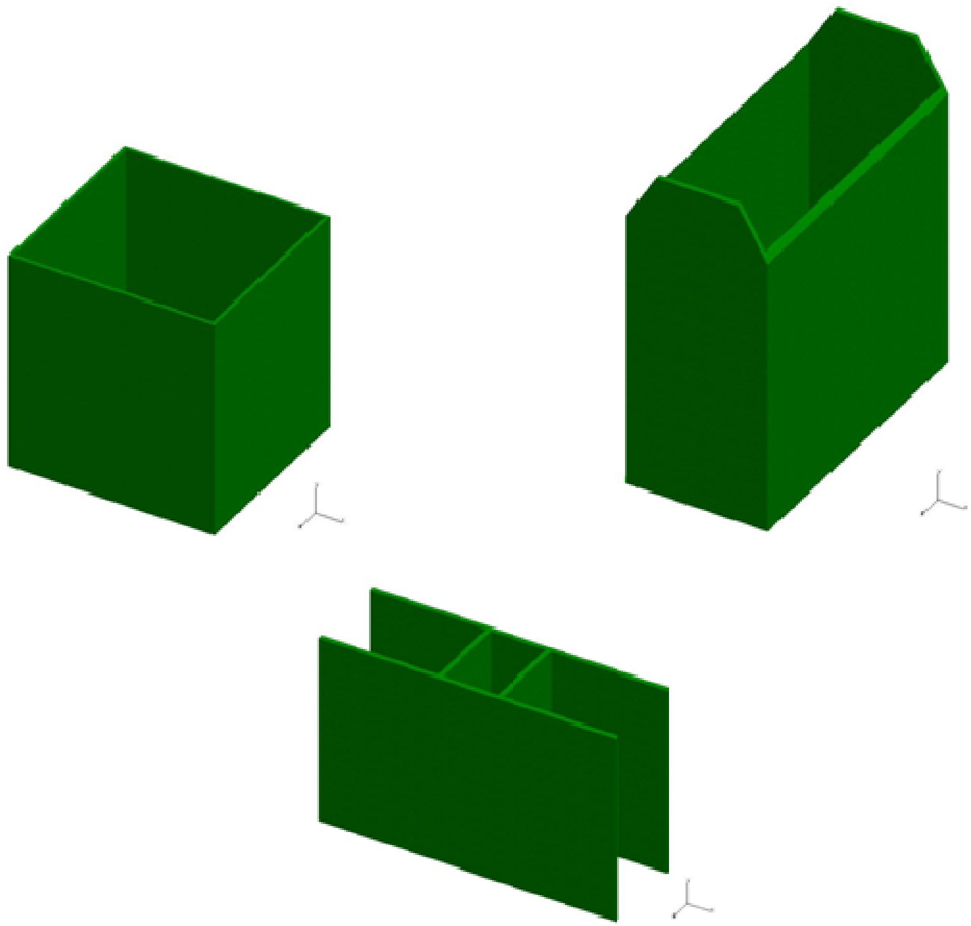

**Figure 10: Box-structure (top left), D-advanced structure (top right), H-structure**

Another main component of the NPSCuL is the P-POD. At this time, only a 3U P-POD is available. For being able to integrate a 5U P-POD as shown in Figure 11, everything will be designed for that case. If the structure can handle the load of a 5U P-Pod (8.09 kg), it will also be able to handle the smaller and lighter 3U P-PODs.


**Figure 11: 5U P-POD**

**Table 3: Properties of the MK III 5U P-POD with respect to the coordinate system shown in Figure 5 [11]**

| Pre-deployed | | | | Post deployed | | | |
|---|---|---|---|---|---|---|---|
| $X_{cg}$ | 0.25 mm | $I_{xx}$ | 1.2361 kg*m$^2$ | $X_{cg}$ | 0 mm | $I_{xx}$ | 0.5428 kg*m$^2$ |
| $Y_{cg}$ | 4.64 mm | $I_{yy}$ | 1.2327 kg*m$^2$ | $Y_{cg}$ | 7.3 mm | $I_{yy}$ | 0.5387 kg*m$^2$ |
| $Z_{cg}$ | 353.1 mm | $I_{zz}$ | 0.0241 kg*m$^2$ | $Z_{cg}$ | 387 mm | $I_{zz}$ | 0.0165 kg*m$^2$ |

## C. DESIGNS

At the beginning of the development progress for an NPSCuL structure three options were under the consideration: H-structure, D-structure, Box-structure. With the exception of the Box-structure, every structure has its own three modifications (Figure 12).

**Open:** only the structure without any cover

**Wrapped:** structure is wrapped by an outer box

**Fully enclosed:** wrapped structure with lid on top

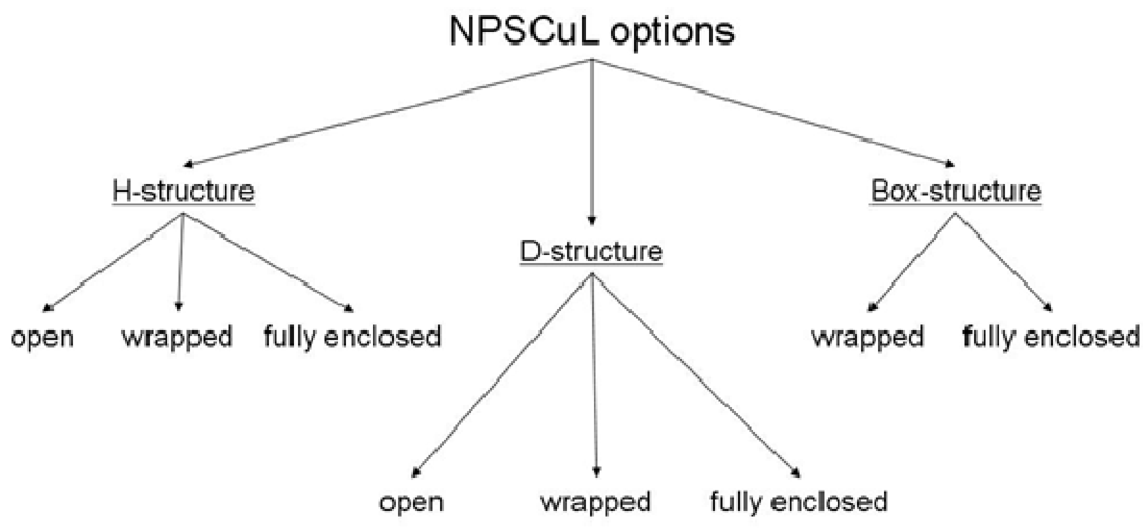


**Figure 12: NPSCuL design options**

After consulting with the P-POD team from CalPoly and the technical director from the California Space Authority, some new facts and ideas were available. It turned out that some options are not feasible and that is why the H-structure was abandoned and the D-structure was modified to the D-advanced structure. All structures are built of ALUMINIUM 7075-T6, which is a high strength Al-Zn-Mg-Cu alloy.

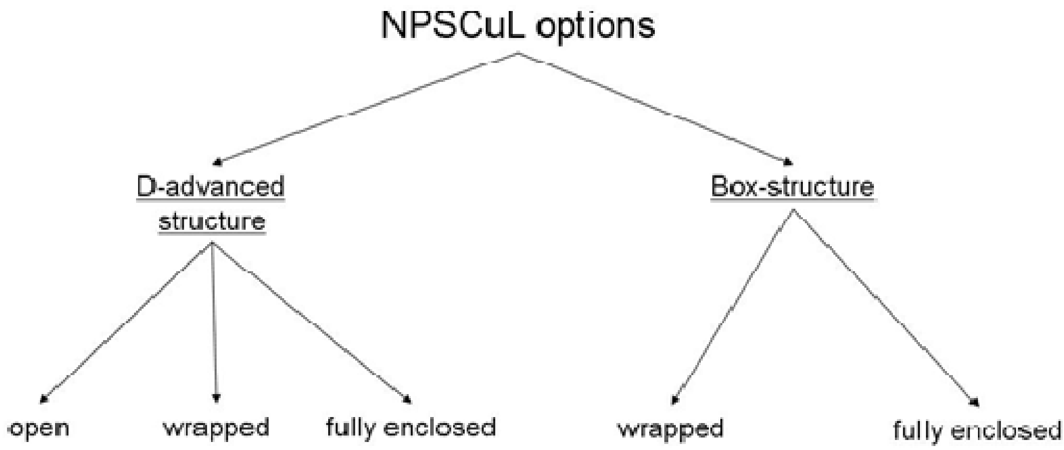


**Figure 13: Final structural NPSCuL options**

### 1. H-Structure

One of the first structural ideas for an NPSCuL was the H-structure. Basically, it consists of four plates which are mounted in the form of an extruded H.

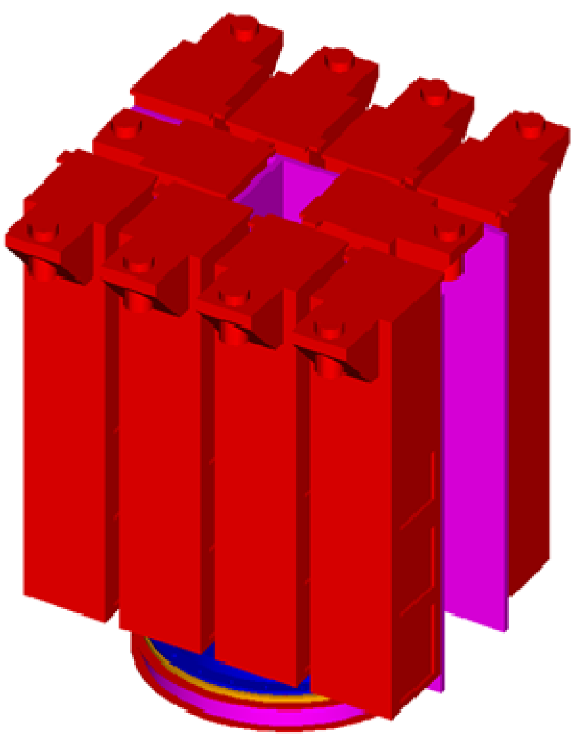

**Figure 14: H-structure (purple) with 10 5U P-PODs**

Figure 14 shows the H-structure with ten 5U P-PODs and the mounted base plate and light band. The P-PODs are mounted on their bottom panel, that is why there has to be a certain sequence for the opening of the doors. The two inner ones have to be opened before the eight outer ones. There might be some contact between the doors, but after opening more than 90 degrees, the CubeSats will be pushed out immediately. In the center of the H-structure is an unused space of 10 by 16 cm. This space can be used for accommodating the electronics and batteries mounted on a plate, which can be moved to any vertical position. Additional weight can also be placed in this storage area to shift the CG to meet launch requirements.

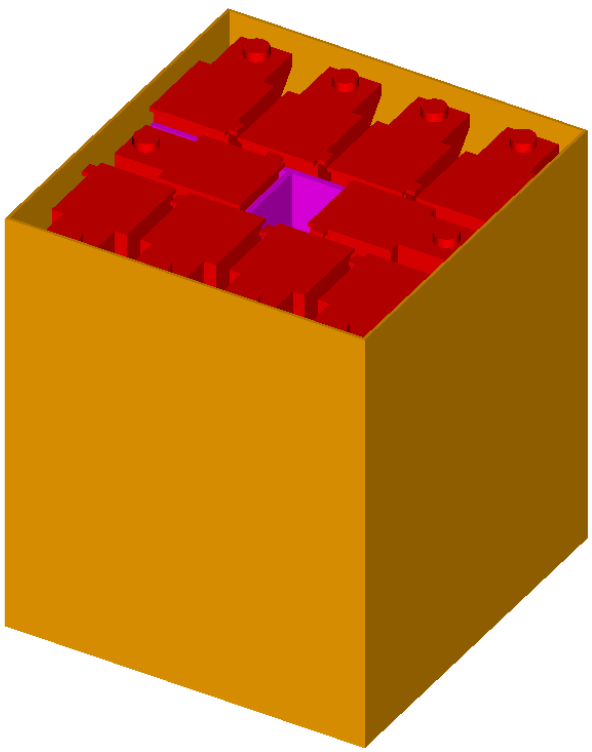

**Figure 15: H-structure wrapped**

The wrapped H-structure contains an outer box, which protects the P-PODs from the LV and vice versa. This box can also be built of AL 7075-T6 or of any other light weight material. The thickness can be under 1 cm, because the box is not a supporting structure.

Figure 16 shows the H-structure fully enclosed. In this case, the outer box has to be a bit thicker than in the wrapped case, because this time it has to carry the lid and the mechanism to open it. Nevertheless, the cover lid can built of another material with different thickness.

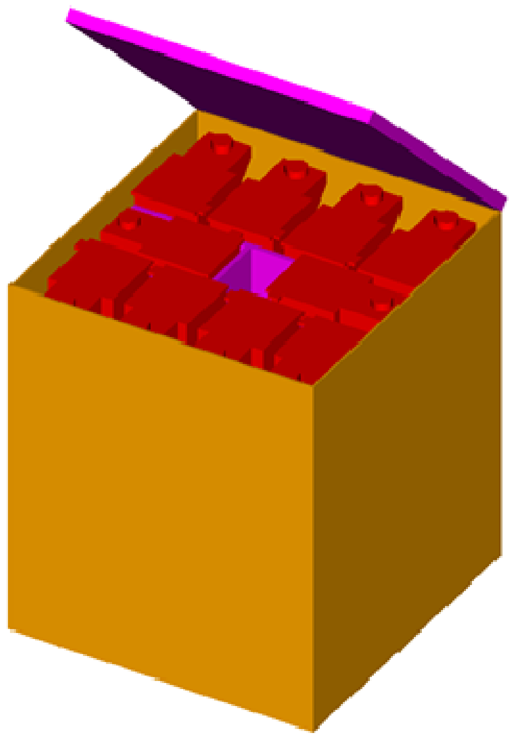

**Figure 16: H-structure fully enclosed**

## 2. Box-Structure

The box-structure follows another principle, the structure is the cover and supporting structure at the same time.  The P-PODs are mounted with their bottom panel facing to the outside.  So the doors will open to the outside as well and there will not be a special opening procedure to avoid any contact.

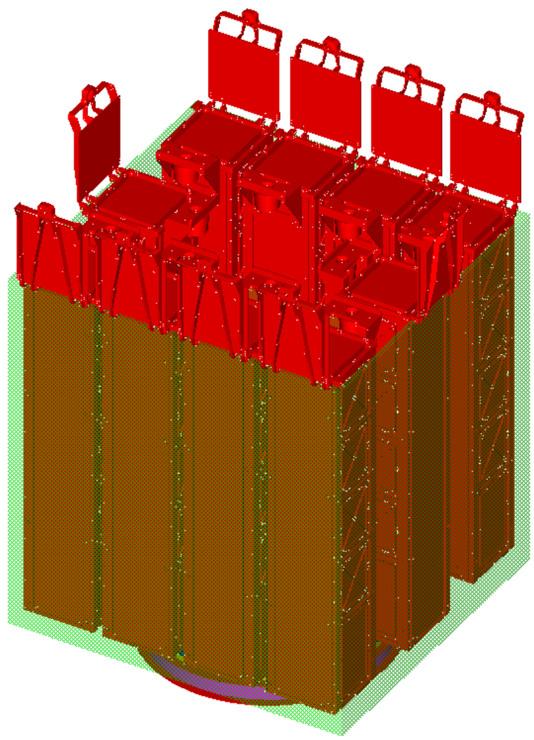

**Figure 17: Box-structure with ten 5U P-PODs**

Inside the box will be a smaller box, which will carry all the electronics and batteries.  This box will also contain additional weight as required to shift the CG.

At this point it is not possible to achieve a fully enclosed box-structure. The green structure fills the ESPA envelope almost completely, so there is not any space left for the supporting structure to carry the lid and its opening mechanism.  Another issue is the design of the P-PODs.  The bottom panel is not a flat surface; the opening mechanism overlaps the box-structure so it is not possible to extract the structure.  Designing a detailed solution for this case will not be part of this technical report.

### 3. D-Structure

The D-structure is the same kind of structure as the H-structure, but now the inner plates are situated at the end of the other two, that is why it looks like an extruded D. The two inner P-PODs are mounted on the bottom panel and will open to the outside. The other eight P-PODs are mounted to the front panel and will open to the inside, which requires a certain order for the opening sequence.

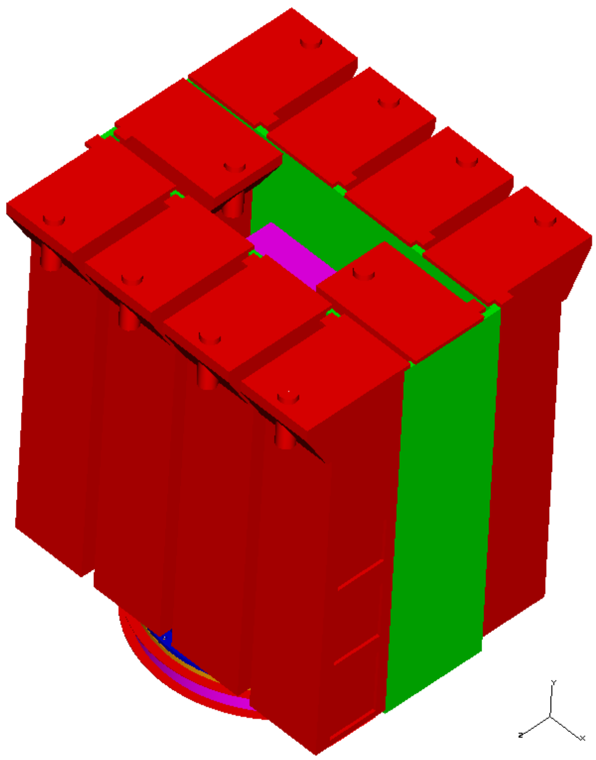

**Figure 18: D-structure open**

As you can see in Figure 12, three options are also available for the D-structure. The options are similar to the H-structure options in that the structure can be open (Figure 18), wrapped by an outer box (Figure 19) or fully enclosed with an outer box and a lid (Figure 20).

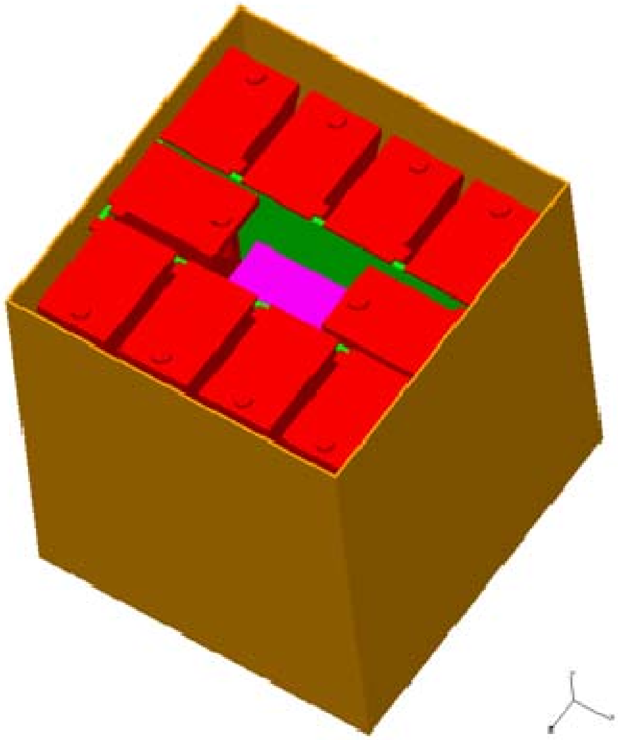

**Figure 19: D-structure wrapped**

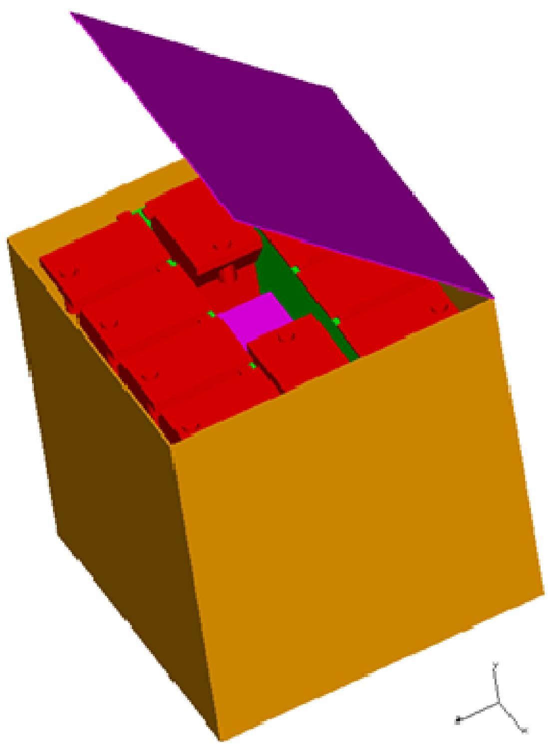

**Figure 20: D-structure fully enclosed**

### 4. Comparison

All together, eight design options for an NPSCuL are available. To maximize the number of prospective users of the NPSCuL, the options have to be compared to figure out a final solution. Therefore, the mass configurations (see Appendix C) are one main issue. Every design has to accomplish the requirements as an SPL, so it has to weigh less than 181 kg. As shown in the table, every option fits into the required mass range but in some cases the margin is very small. That means there is not a lot of additional weight available to get a CG requested by the space program manager.

Table 4 shows the advantages and disadvantages concerning the structural requirements of the NPSCuL. As it was mentioned before, every option fits into the ESPA volume and is below the maximum mass. The only structure that has the capability to carry a 2U by 2U CubeSat is the box-structure. The three P-PODs in one corner can easily be replaced by a bigger P-POD. No other structures have enough clearance to the ESPA envelope. Every structure is deployable, because a Lightband can be attached easily. They also are hot ready, so the program manager just has to add the CubeSats and program the software for the launch sequence. Another important issue is the ease of assembly. Based on Table 4 and Figure 14, the hole inside of the H-structure is very small; therefore you will need very small tools. The fully enclosed box-structure is also hard to assemble, because it will be very difficult to put a lid and an opening mechanism on top. The last two requirements are the capability to be mass reconfigurable and to carry the electronics. Additional mass and the electronics are arranged inside of the hole of the H-structure or inside of an electronics box in the Box- or D-structure.

**Table 4: Advantages and disadvantages of the design options**

| | H open | H wrapped | H fully enclosed | D open | D wrapped | D fully enclosed | box wrapped | box fully enclosed |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| Overall Mass | 131.0 | 160.4 | 163.5 | 98.6 | 127.9 | 131.1 | 155.9 | |
| Unused mass *(4)* | 50.0 | 20.6 | 17.5 | 82.4 | 53.1 | 49.9 | 25.1 | |
| Fits into ESPA volume? | Y | Y | Y | Y | Y | Y | Y | Y |
| Could launch 2Ux2U CubeSats | N | N | N | N | N | N | Y | Y |
| Deployable? | Y | Y | Y | Y | Y | Y | Y | Y |
| Ease of assembly | *1* | *1* | *1* | Y | Y | Y | Y | N *(2)* |
| Hot ready? | Y | Y | Y | Y | Y | Y | Y | Y |
| Mass reconfigurable? | *3* | *3* | *3* | Y | Y | Y | Y | Y |
| Space for electronics | *3* | *3* | *3* | Y | Y | Y | Y | Y |
| | | | | | | | | |
| Notes: | *1* | small tools are needed | | | | | | |
| | *2* | difficult to put on a lid | | | | | | |
| | *3* | only inside of the structure (10x16 cm) | | | | | | |
| | *4* | total ESPA payload mass = 181kg | | | | | | |

## 5. Advanced D-Structure

The only problem with the D-structure is the certain sequence for opening of the P-PODs and that is why, in addition to the advice offered by the CalPoly team, an advanced D-structure was designed. Therefore the upper edges of the original D-structure were modified to provide that the eight P-PODs on the side can be turned. That means finally all the P-PODs will open to the outside, so a special launch sequence is no longer necessary. Figure 21 shows the open D-advanced structure (green), the ten 5U MK III P-PODs (red) and the attached base plate and Lightband. Inside of the structure will be an electronics box as well.

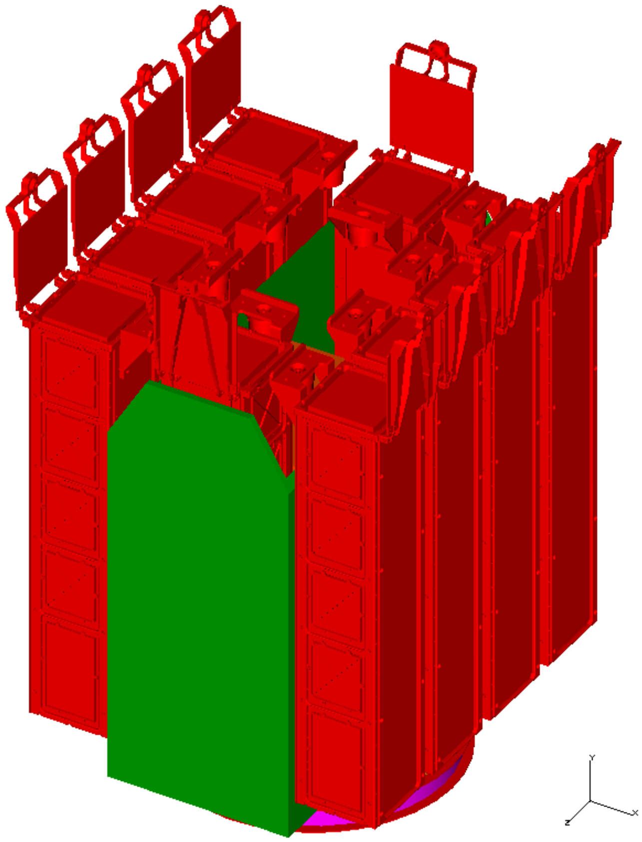

**Figure 21: Open D-advanced structure**

There will be three options for the D-advanced structure as well; open, wrapped, and fully enclosed. They have the same shape as the D-structure, only the structure itself is different.

## D. STRESS ANALYSIS

### 1. Simple model

For getting a first overview of the tensile stress of the final structure a simple model is designed and meshed in I-DEAS 12. With the results of this model, it is easy to figure out the critical areas of the structure. At the beginning, the worst case is simulated by adding ten forces in every direction on ten nodes (Figure 22). Equation (1.1) shows the definition of the overall force, which includes a maximum acceleration of 10 g (as required by the DoD STP) and a mass of 80.9 kg for the ten 5U P-PODs. This Figure also shows another simplification, the grounding points are situated in the corners of the structure.

$$F = m * a \tag{1.1}$$

$$m = 10 * 8.09\, kg \tag{1.2}$$

$$a = 10\, g \tag{1.3}$$

$$F = 7{,}936.3\, N \tag{1.4}$$

$$\underline{\underline{F_N = \frac{F}{10} = 793.4\, N}} \tag{1.5}$$

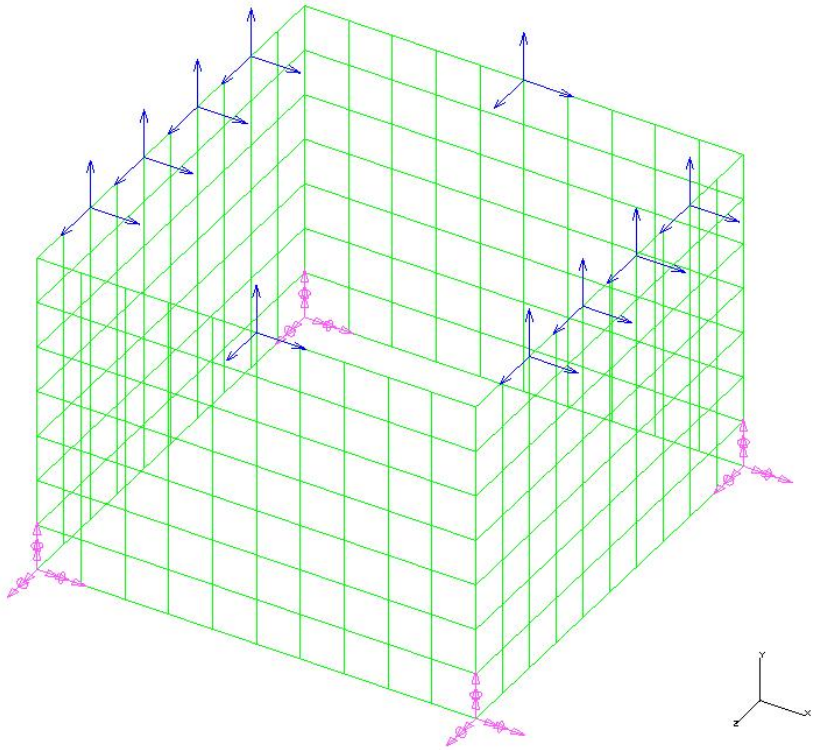


**Figure 22: Simple model with 10 forces**

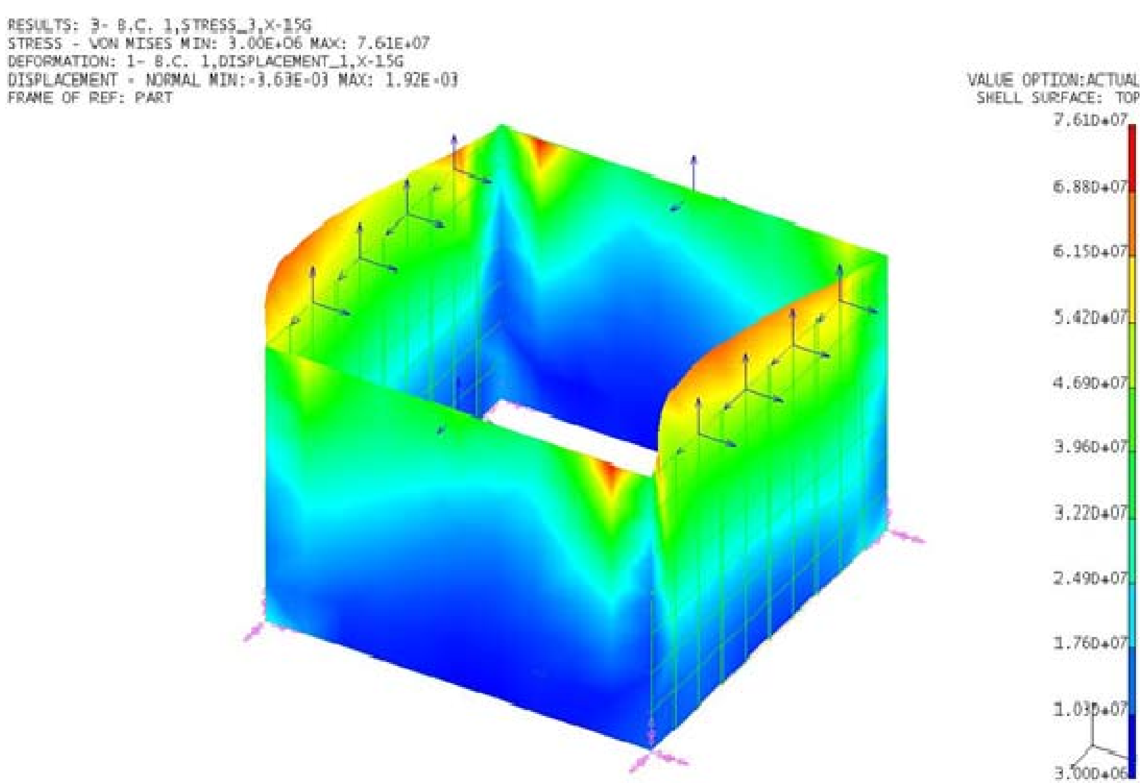


**Figure 23: Solution simple 5U-model with 10 forces**

As shown in Figure 23, the maximum stress is on the top edges of the structure. That is why the simple structure is modified and the ten forces are replaced with 60 forces, which are representing the real forces of the 60 mounting bolts.

$$\underline{\underline{F_N = \frac{F}{60} = 132.3\,N}} \tag{1.6}$$

As a result of the uniformly distributed forces the maximum of the stress is now at the grounding points in the four corners (Figure 24). This conclusion was verified by using smaller elements where the maximum stress changed slightly, but the locations remained the same. Finally the simple model shows, that the grounding points are the main critical stress areas of the structure.

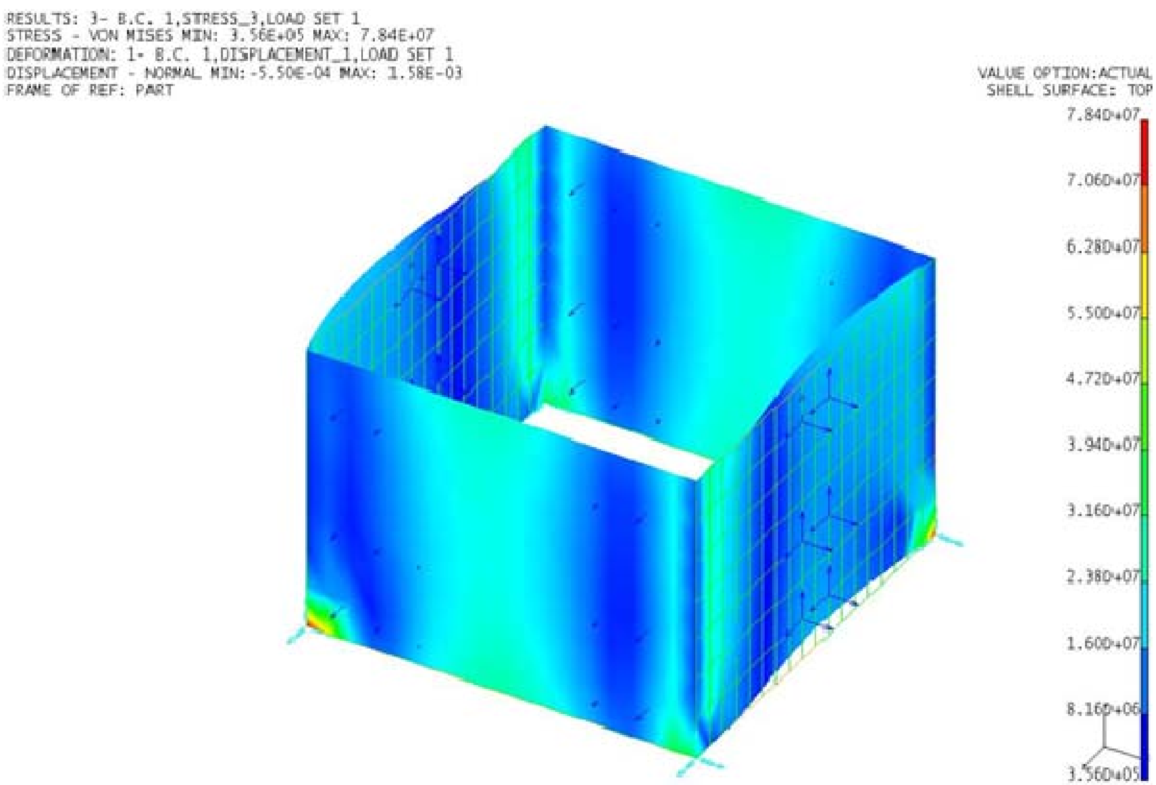


**Figure 24: Solution simple 5U-model with 60 forces**

### 2. Box-structure

The calculations of III.D.1 show that the bottom of the structure is the critical area resulting from the applied forces. That is why the sides of the structure are meshed with 2 cm long elements and the bottom area is meshed with a changeable number of elements. The P-PODs are realized with the lumped mass elements (8.09 kg each) and connected to the structure by rigid body elements.

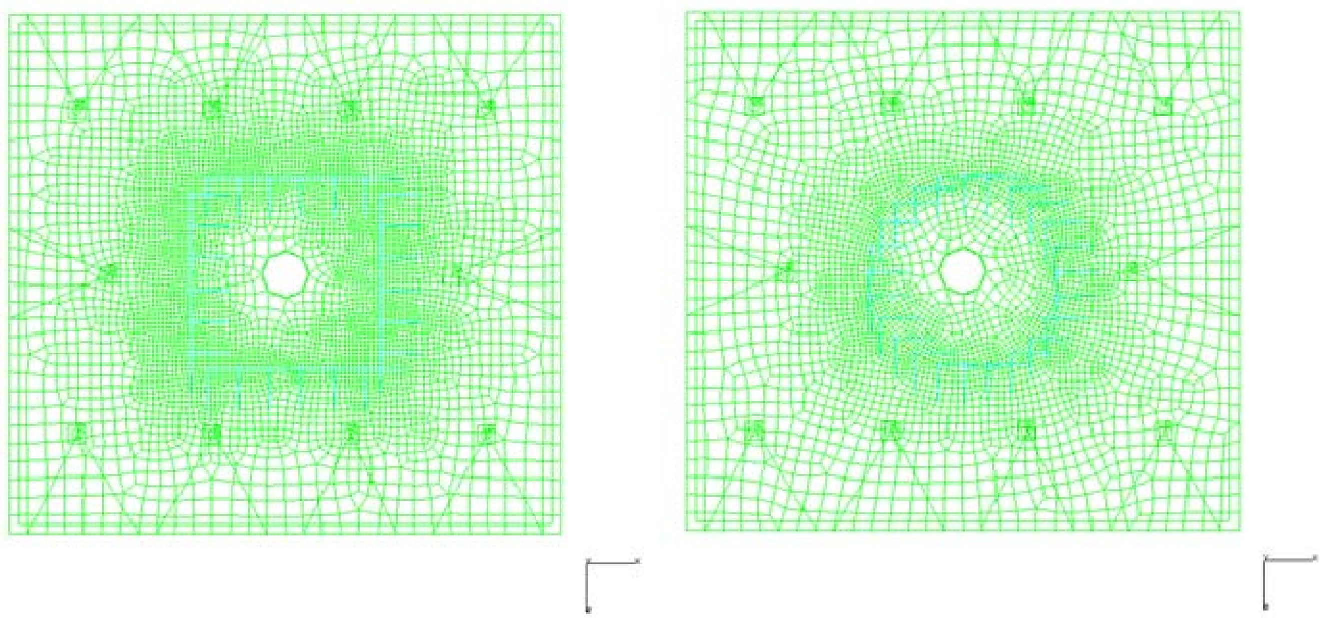

**Figure 25: Meshed box-structure with square (left) and circle (right) bolt pattern**

#### *a) Box-structure with square bolt pattern*

At the beginning of the stress analysis, a shell thickness of 10 mm and 20 bolts were used, resulting in each edge having 5 bolts for the connection between the structure and the baseplate. The element length is 2 cm, but each edge has 20 elements to ensure a better resolution. Compared to the maximum tensile stress of AL 7075-T6, which is $4.82 \times 10^8$ N/m$^2$, this set-up (Figure 26) results in an unacceptable level of stress ($7.89 \times 10^8$ N/m$^2$).

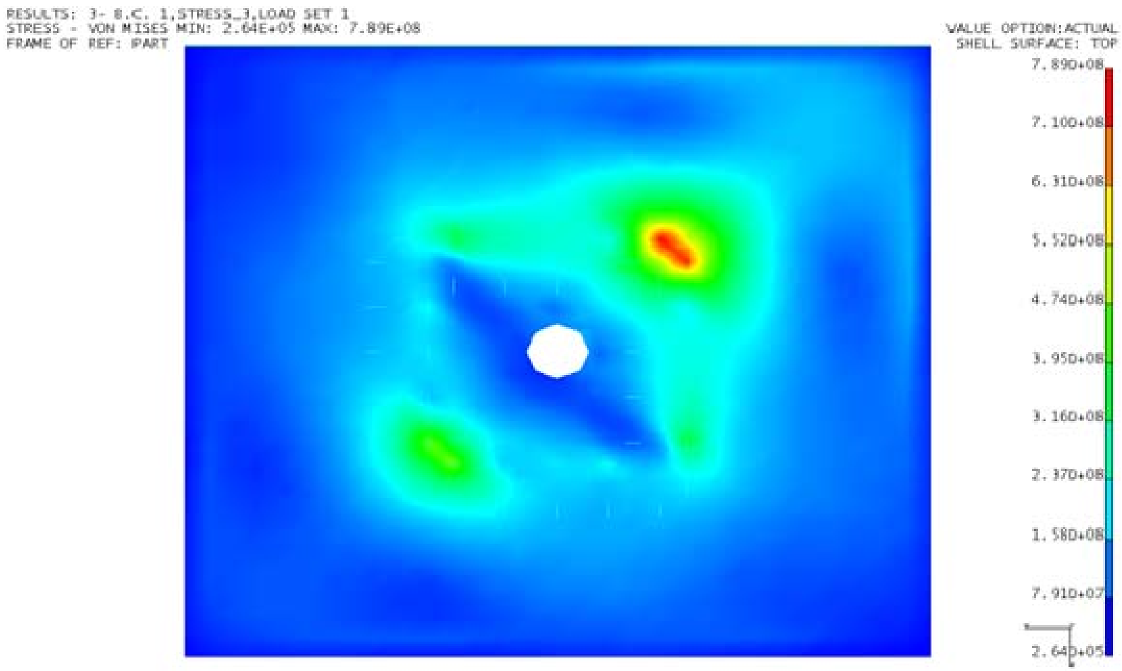


**Figure 26: Box-structure with square bolt pattern, 10mm shell, 20 bolts, 20 elements**

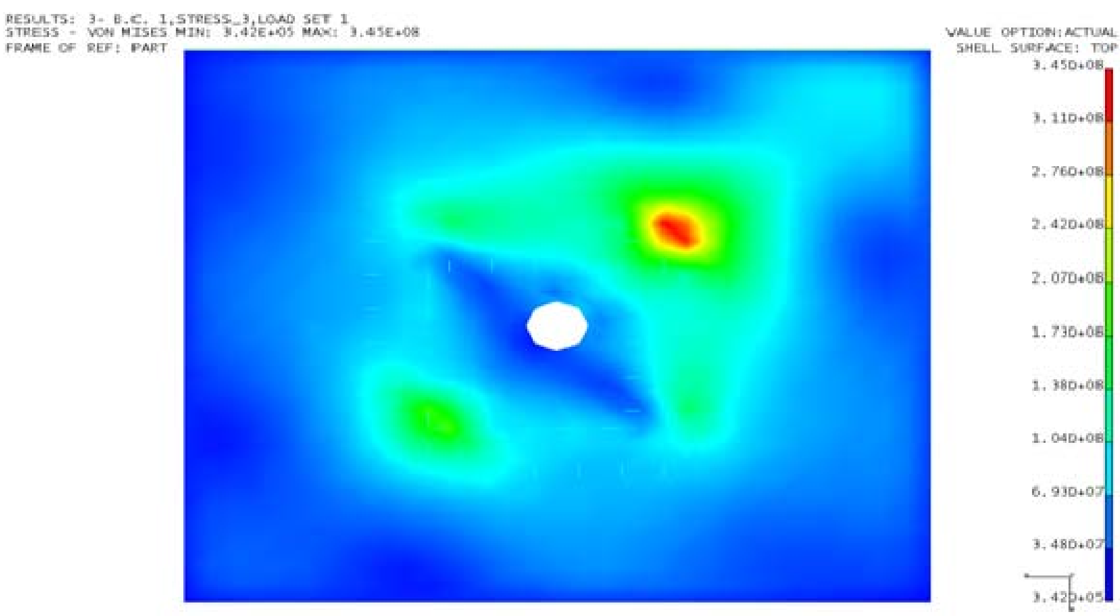


**Figure 27: Box-structure with square bolt pattern, 15mm shell, 24 bolts, 24 elements**

To determine the reason why the stress is so high, another set-up is meshed. This time 24 bolts are used, which might create a lower stress because this arrangement will share the reaction forces better. The shell thickness is 15 mm. Figure 27 displays the result , this time the stress is only half of the amount of the results in Figure 26. In this case, the element length on each edge is 0.875 cm. To get a better resolution the H-method from II.D is used. The software was not able to create more than 72 elements on each edge of the bolt square (0.29 cm), this indicates a maximum stress of $4.73 * 10^8$ N/m$^2$, which is close to the maximum of AL 7075-T6 ($4.82 * 10^8$ N/m$^2$).

If a lower stress compared to the maximum allowed stress is necessary, a shell thickness of 20 mm can be used. This results in a maximum stress of $2.61 * 10^8$ N/m$^2$ (Figure 29).

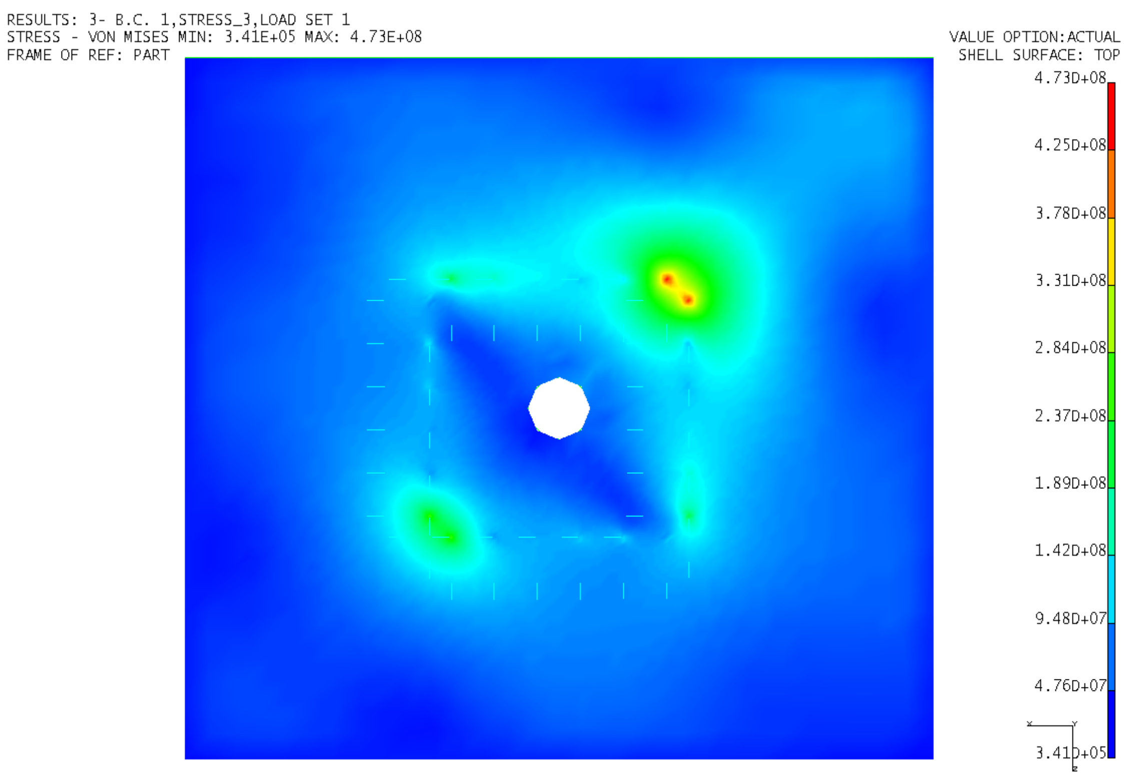


**Figure 28: Box-structure with square bolt pattern, 15mm shell, 24 bolts, 72 elements**

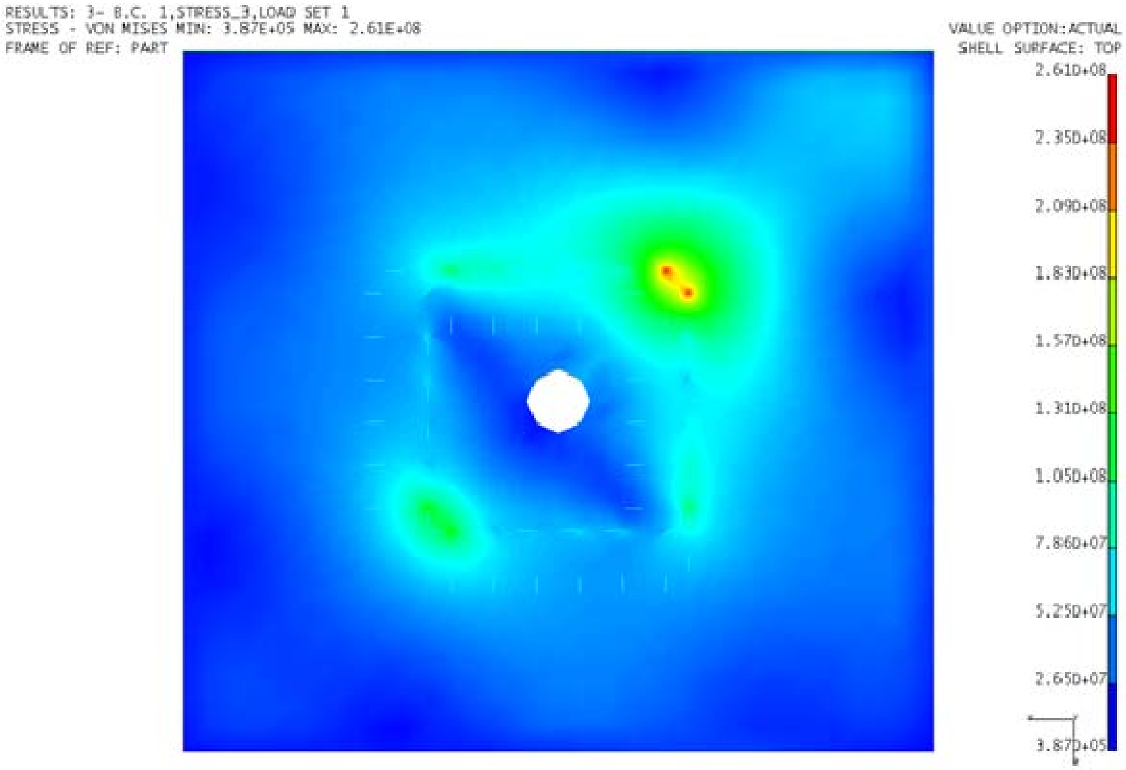


**Figure 29: Box-structure with square bolt pattern, 20mm shell, 24 bolts, 72 elements**

### *b) Box-structure with circle bolt pattern*

Another way to mount the structure to the base plate is the circle bolt pattern. The following pictures (Figure 30 - Figure 32) show the results of different set-ups. Similar to the results with the square bolt pattern, the stress is lower when a thicker shell is used. To get a better resolution, the H-method is used as well.

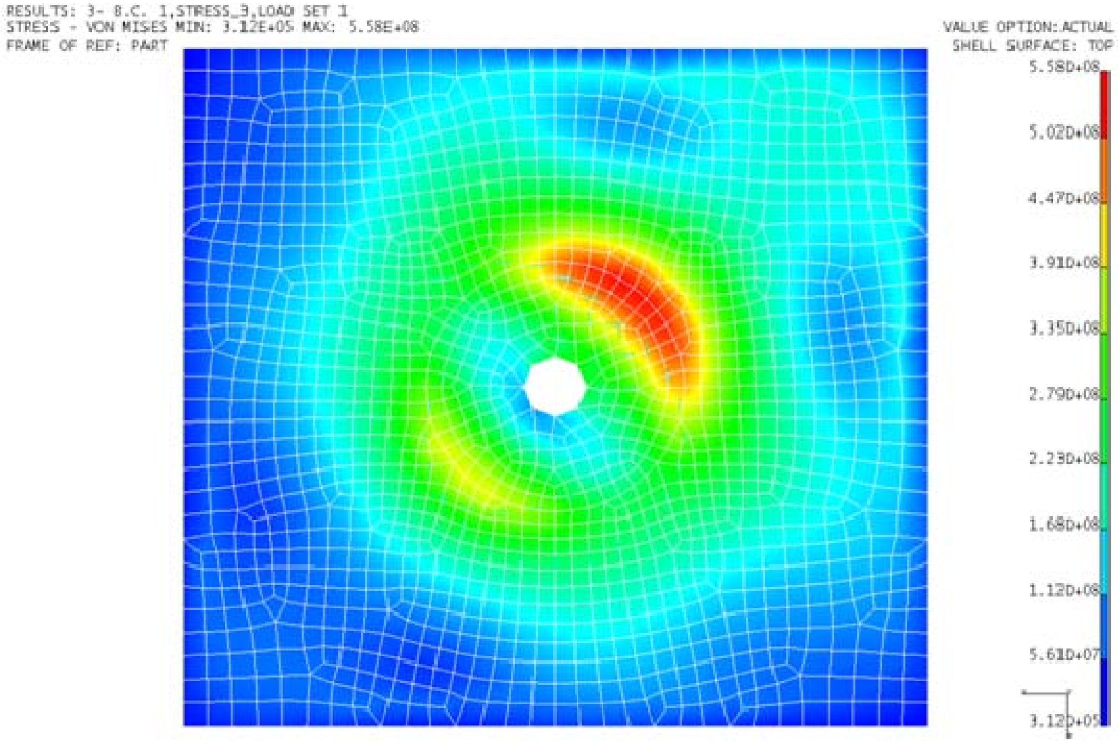


**Figure 30: Box-structure with circle bolt pattern, 10mm shell, 24 bolts, 48 elements**

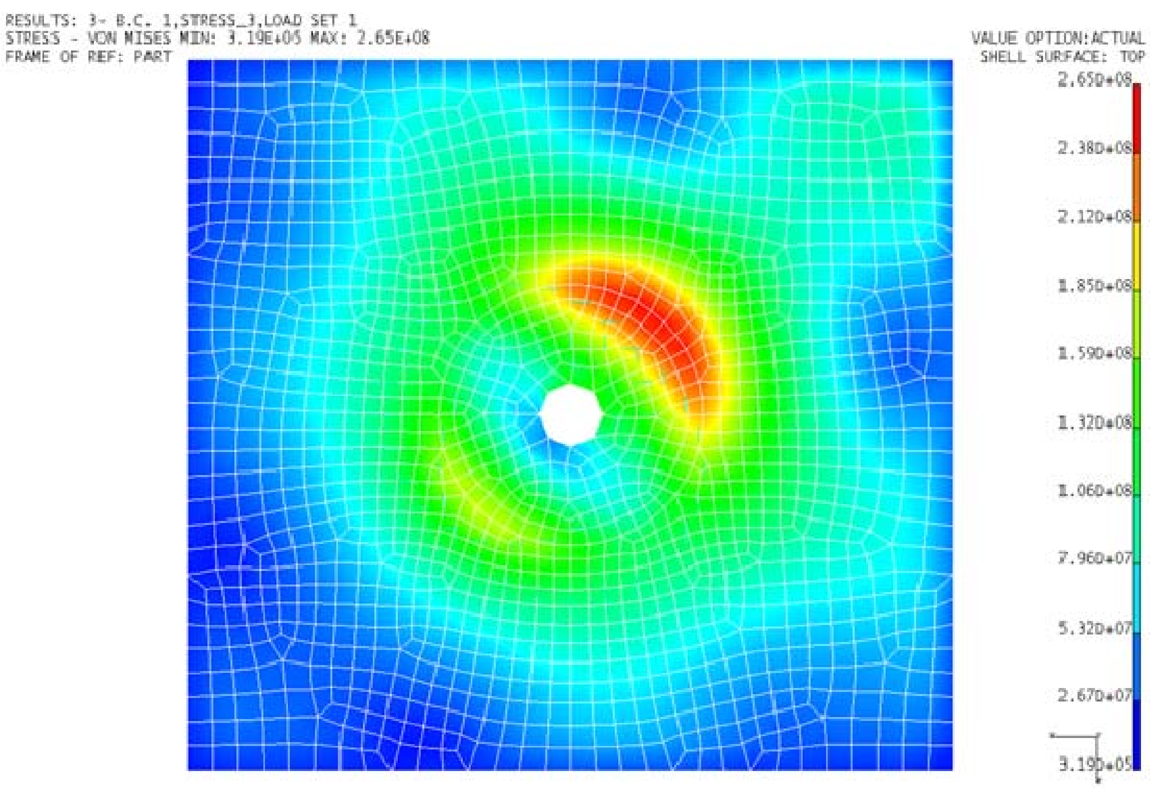


**Figure 31: Box-structure with circle bolt pattern, 15mm shell, 24 bolts, 48 elements**

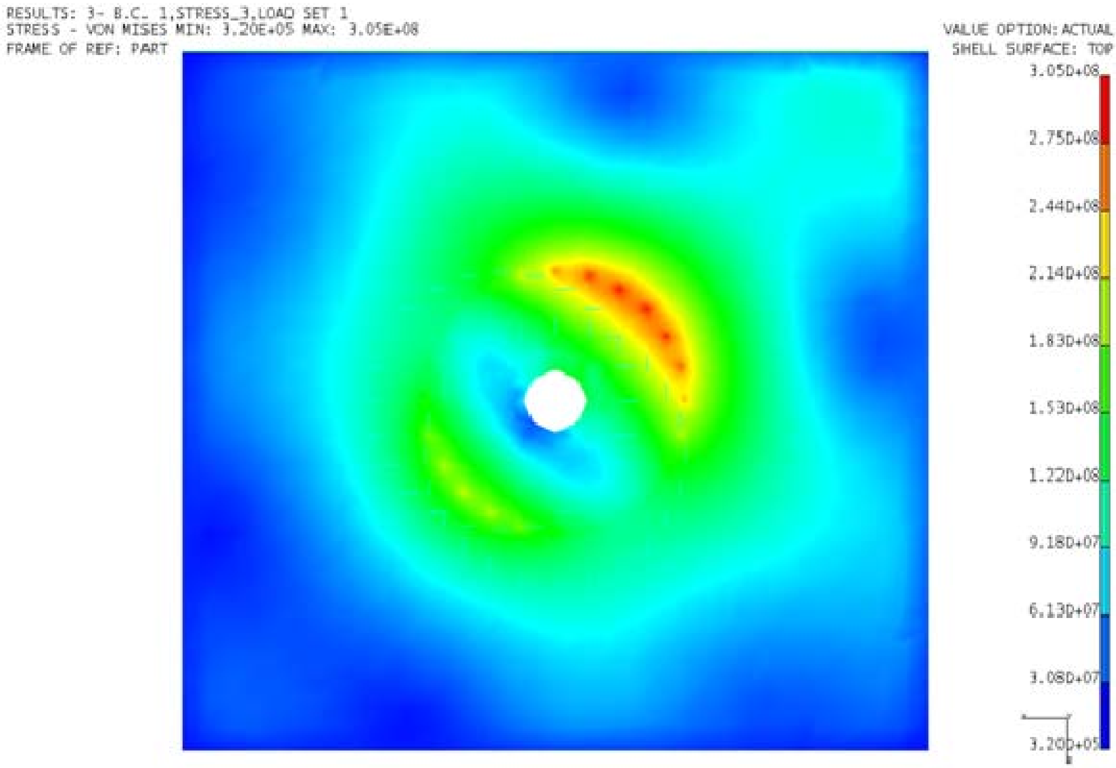


**Figure 32: Box-structure with circle bolt pattern, 15mm shell, 24 bolts, 216 elements**

### *c) Box-structure comparison*

The shown results display the main difference between the square and the circle bolt pattern. The maximum stress using the square bolt pattern is concentrated on the two bolts in the corner, while the maximum stress using the circle bolt pattern is situated at six bolts. The force distributes over a larger area resulting in lower stress.

As a result of using the H-method and different shell thicknesses, it is possible to figure out the best structural design for the box-structure. Figure 33 shows the comparison between different set-ups. The red line displays the maximum allowed stress of AL 7075-T6.

It was expected that the curves would flatten with an increasing number of elements (Figure 33). The difference between every step gets smaller, but the curves do not end in a plateau. Maybe smaller elements have to be created, but the software used was not able to exceed 288 elements on the square.

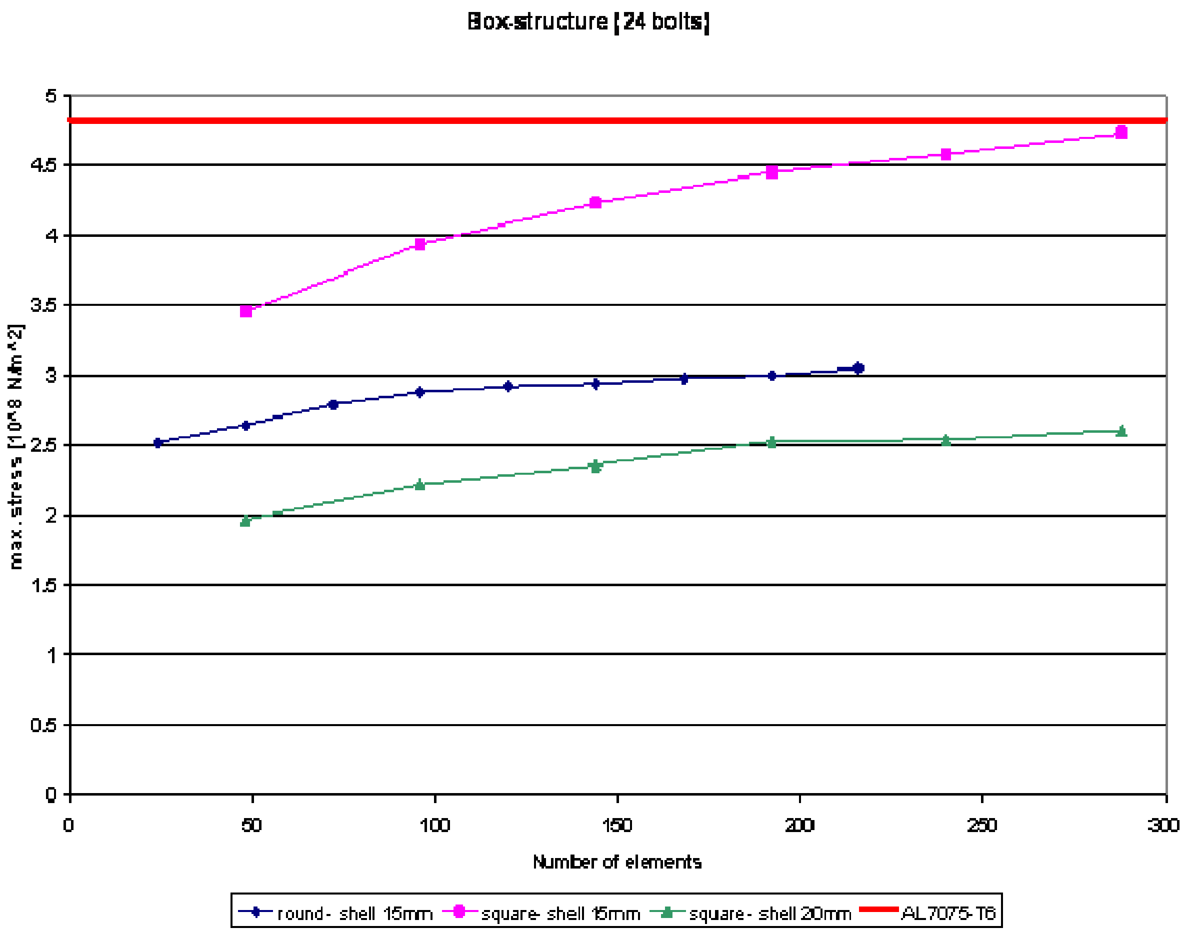


**Figure 33: Maximum stress of box-structure**

The bottom line of this comparison is that three set-ups can be considered. The set-up with the square bolt pattern and a shell thickness of 15 mm is getting too close to the maximum and it is not clear if it will have to increase further with an increasing number of elements. The set-up with the square bolt pattern and a 20 mm shell is far away from the maximum, but the circle set-up with the 15 mm shell will be lighter and

is also far away from the maximum. Another issue is that the acceleration used during calculation was 15 g, instead of the required 10 g. The resulting acceleration using 15 g in each direction is 25.98 g, giving the simulation a factor of safety of 1.5.

### 3. D-advanced structure

The mesh of the D-advanced structure is similar to the box-structure. The side panels are meshed with 2 cm long elements and the P-PODs are mapped assuming lumped mass and rigid body elements. There are also two different bolt patterns feasible.

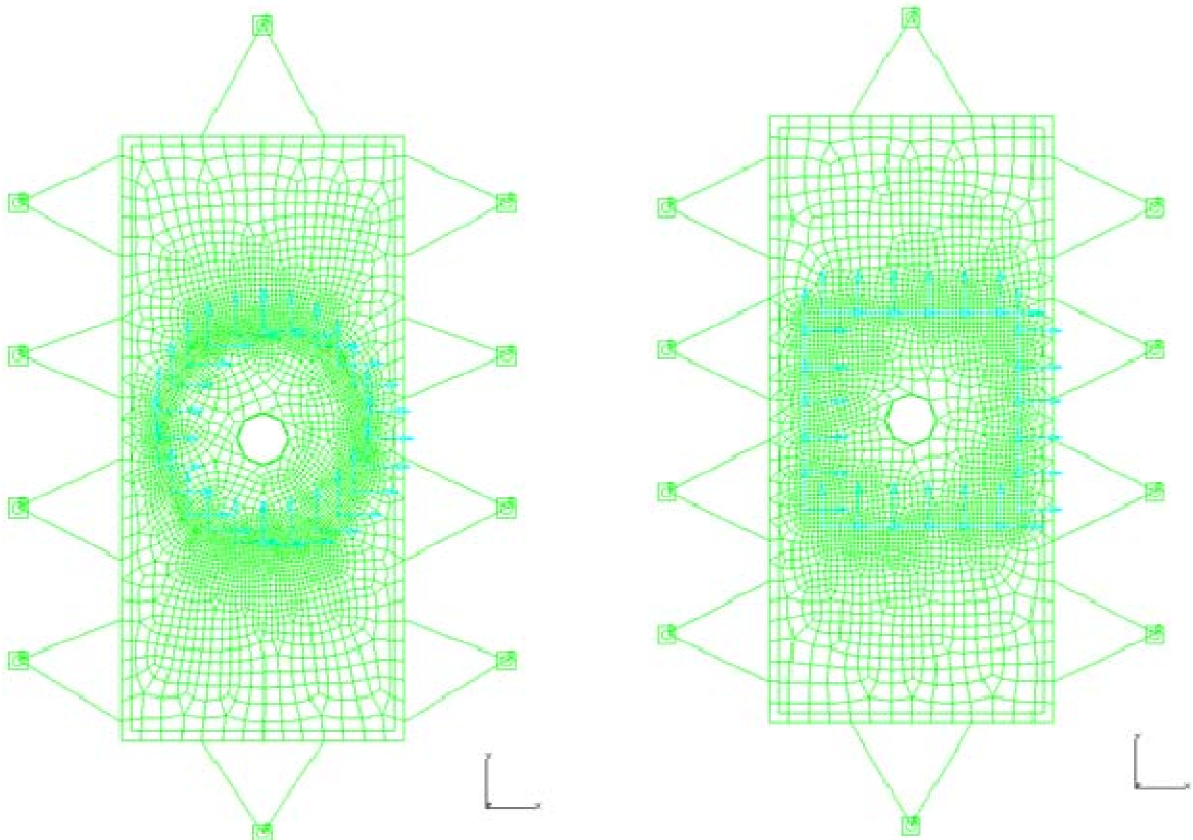

**Figure 34: Meshed D-advanced structure with circle (left) and square (right) bolt pattern**

### a) D-advanced structure with square bolt pattern

The procedure for creating FE-models for the D-advanced structure is similar to the box-structure. Starting with 16 bolts and a 10 mm shell (Figure 35) showed that a larger number of bolts is necessary.

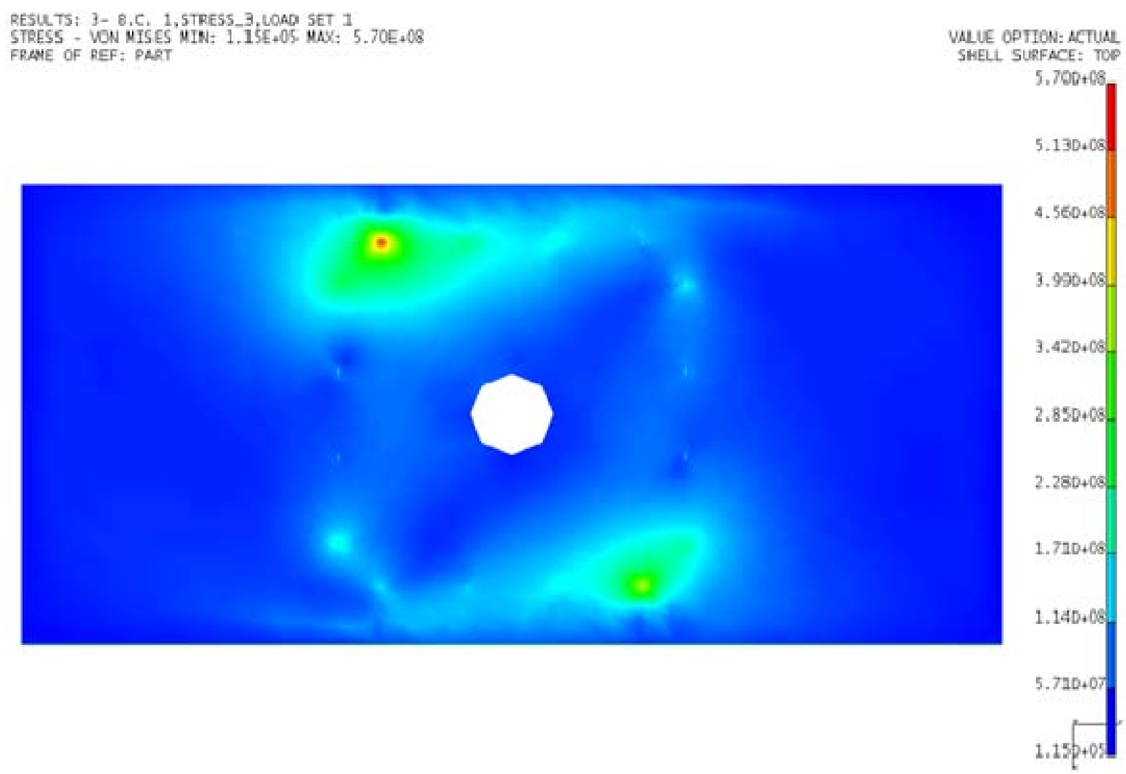


**Figure 35: D-advanced structure with square bolt pattern, 10mm shell, 16 bolts, 48 elements**

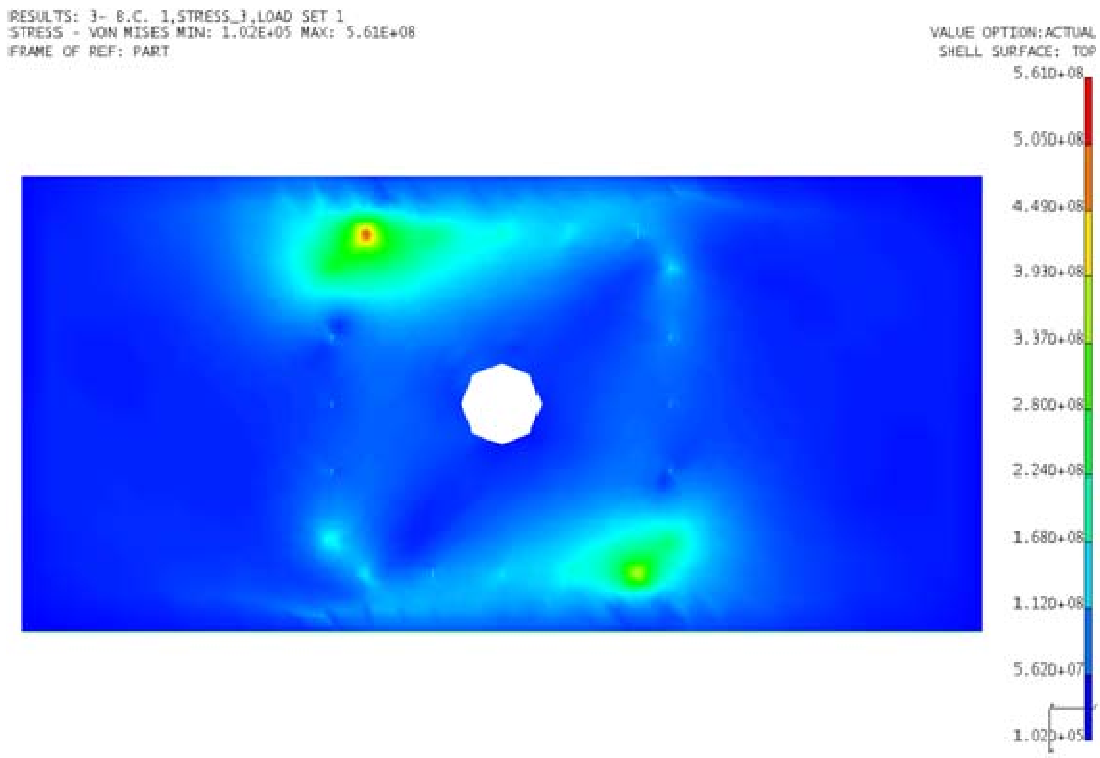


**Figure 36: D-advanced structure with square bolt pattern, 10mm shell, 20 bolts, 50 elements**

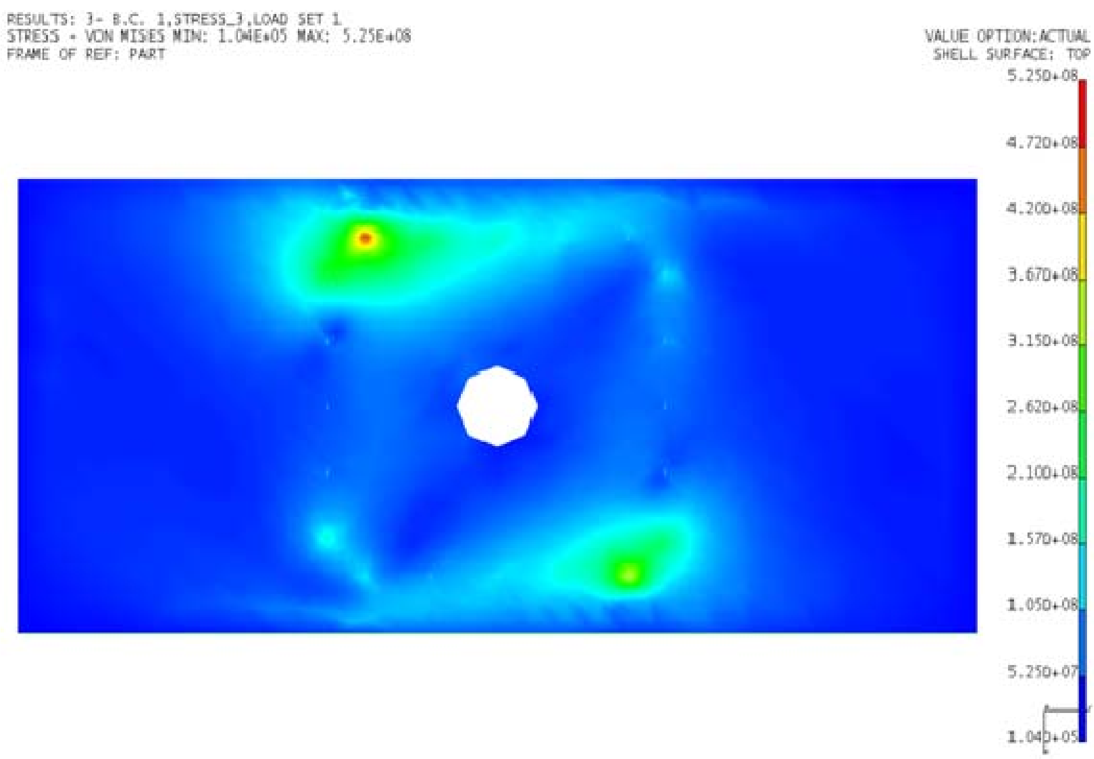


**Figure 37: D-advanced structure with square bolt pattern, 10mm shell, 24 bolts, 36 elements**

Finally, a square bolt pattern with 24 bolts, 6 on each edge, is used (Figure 37). The maximum stress is $5.25*10^8$ N/m$^2$, which is a bit higher than the allowed stress. That is why the shell thickness is modified to 15 mm.

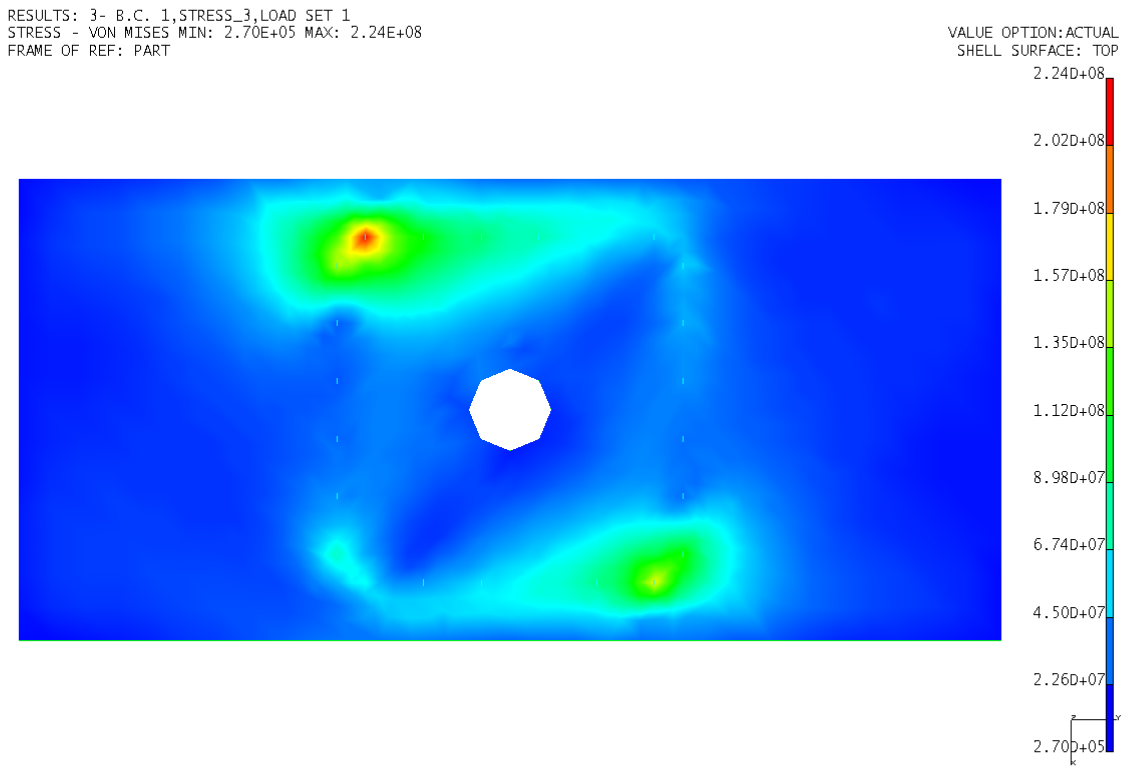


**Figure 38: D-advanced structure with square bolt pattern, 15mm shell, 24 bolts, 24 elements**

For getting better resolution, the H-method is used again. As shown in Figure 39, the maximum stress has changed for the solution with only one third the number of elements. Once again the software was not able to mesh the edges tighter, that is why no more FE-models could be drawn up. Nevertheless, the maximum stress is $2.8*10^8$ N/m$^2$, which is substantially below the maximum allowed.

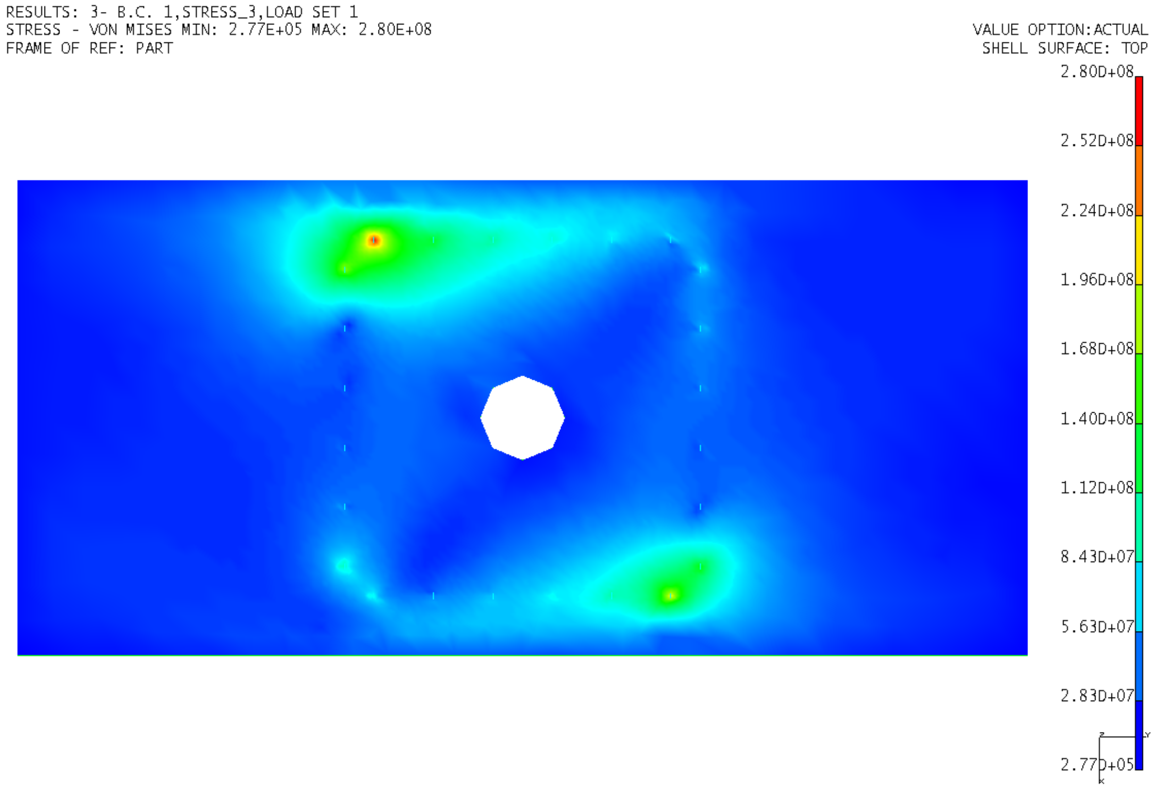


**Figure 39: D-advanced structure with square bolt pattern, 15mm shell, 24 bolts, 72 elements**

### *b) D-advanced structure with circle bolt pattern*

It is also possible to mount the D-advanced structure with a circle bolt pattern. This time, 24 bolts and shell thicknesses of 10 mm and 15 mm were used. The H-method of defining smaller elements is used again, selecting element lengths between 1.3 cm (48 elements) and 0.3 cm (216 elements). The acceleration for these static FE-models is 15 g in each direction at the same time. The results are displayed in Figure 40 to Figure 43.

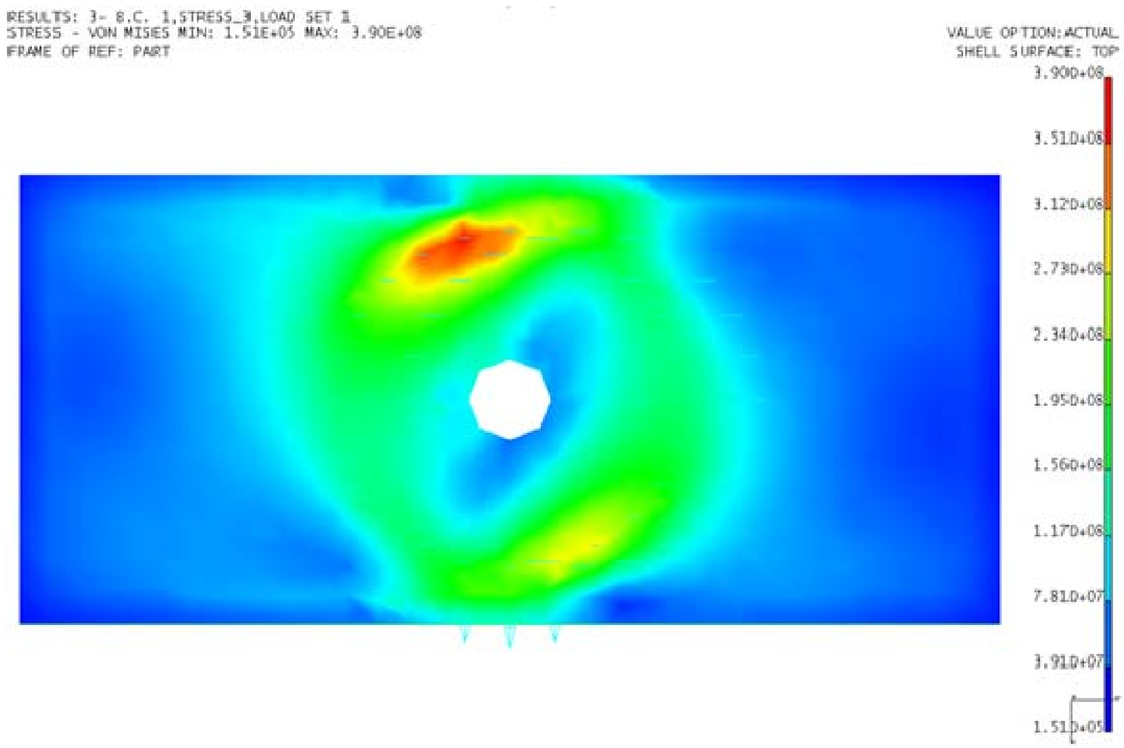


**Figure 40: D-advanced structure with circle bolt pattern, 10mm shell, 24 bolts, 48 elements**

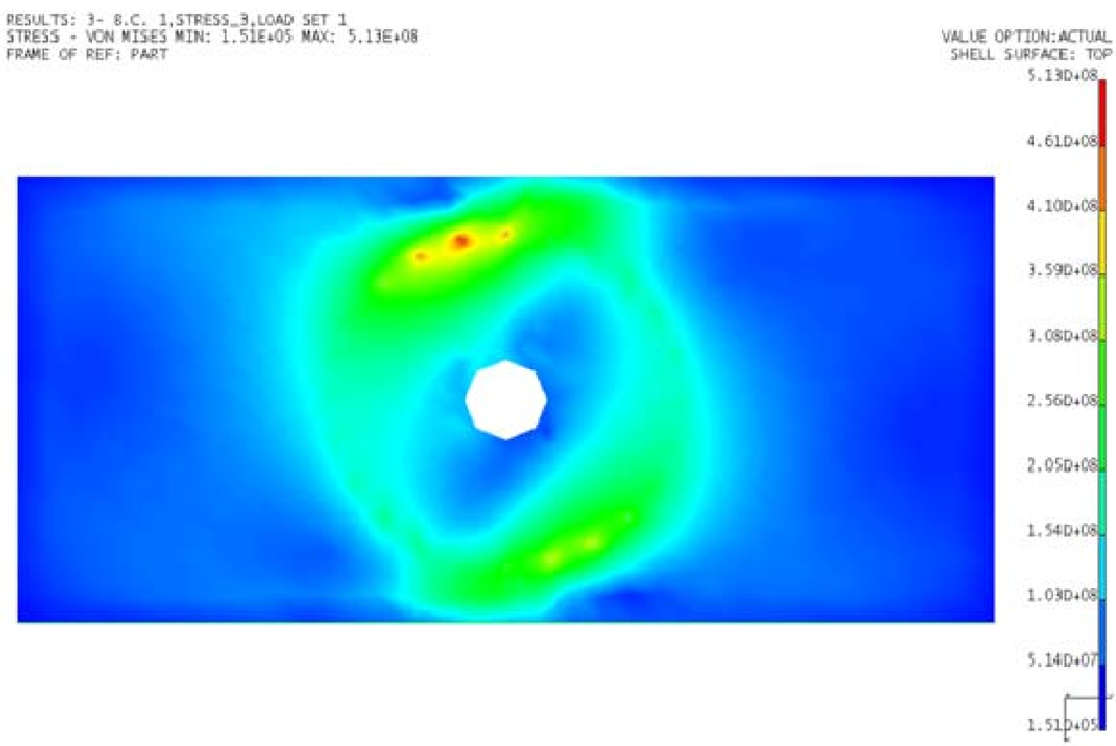


**Figure 41: D-advanced structure with circle bolt pattern, 10mm shell, 24 bolts, 216 elements**

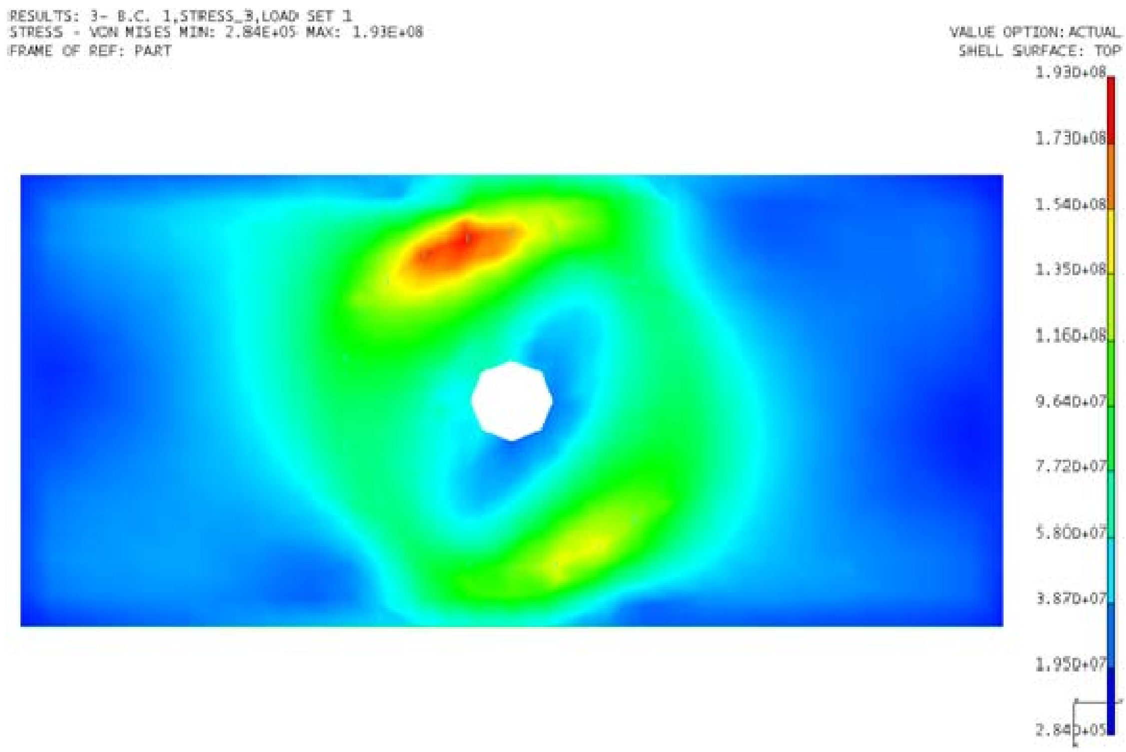


**Figure 42: D-advanced structure with circle bolt pattern, 15mm shell, 24 bolts, 48 elements**

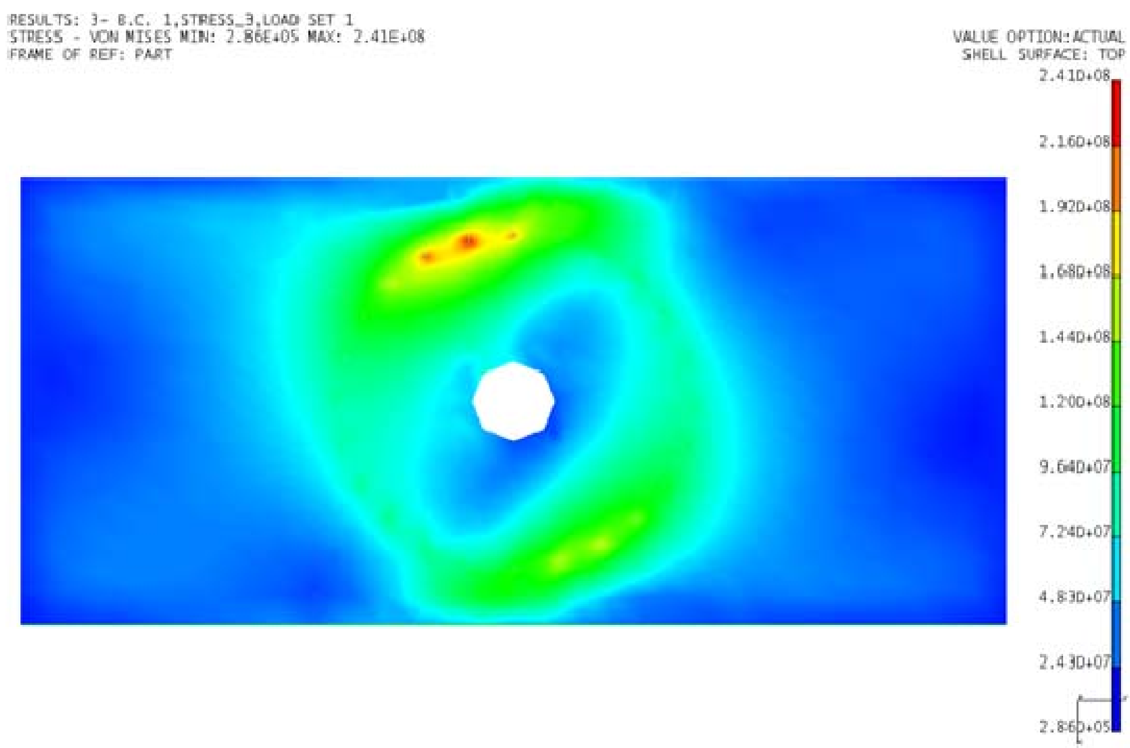


**Figure 43: D-advanced structure with circle bolt pattern, 15mm shell, 24 bolts, 216 elements**

### c) *D-advanced structure comparison*

The displayed results of the D-advanced structure are similar to the box-structure. The maximum stress at the square bolt pattern is located at one bolt in the corner, while the maximum stress of the circle bolt pattern is situated at three bolts and allocated over a bigger area.

Figure 44 displays the results for a different number of elements and a different shell thickness. The red line is once again the maximum allowed stress of the used material AL 7075-T6. The curves flatten out with an increasing number of elements, but they do not end in a plateau. A FE-model with smaller elements was not possible to be meshed by the software.

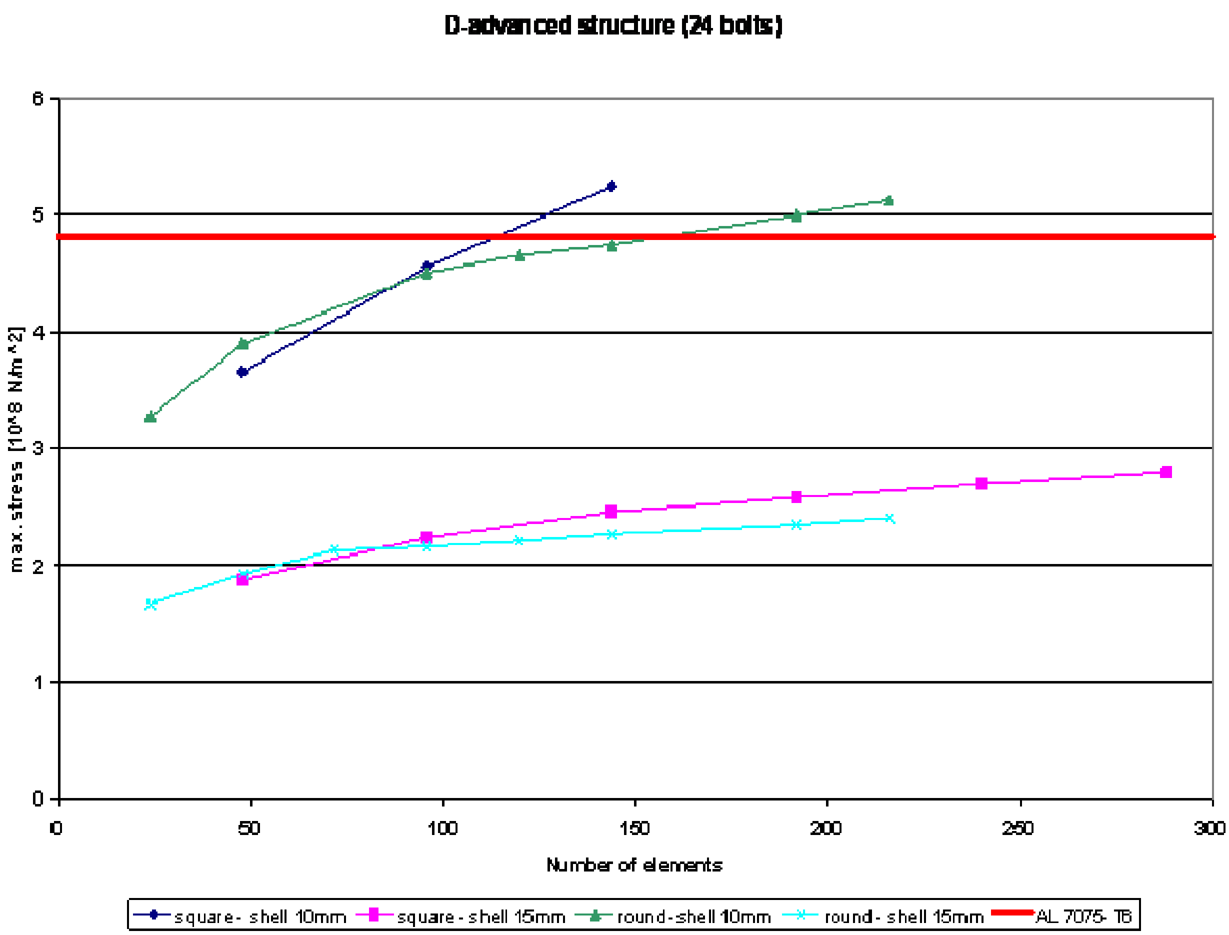


**Figure 44: Maximum stress of D-advanced structure**

The set-ups with a shell thickness of 10 mm results in an unacceptable level of stress. That is why the square or circle bolt pattern with a shell thickness of 15 mm should be used. Their curves flatten out with an increasing number of elements and it is expected, that they will not come close to the maximum allowed stress.

For these static FE-models, an acceleration of 15 g in each direction at the same time is used (magnitude of 25.98 g). This is a adequate factor of safety compared to the ESPA required value.

## E. FREQUENCY ANALYSIS

The previous solutions only considered the static loading created by an acceleration of 15 g. Another important issue is the fundamental frequency, which is required to be at least 35 Hz but 50 Hz will be used resulting in a higher factor of safety.

**Table 5: Fundamental Frequencies**

| | Mode 1 [Hz] |
|---|---|
| Box-structure round, 15mm, 24 bolts, 216 elements | 21.05 |
| Box-structure square, 20mm, 24 bolts, 288 elements | 36.59 |
| D-advanced round, 15mm, 24 bolts, 216 elements | 32.32 |
| D-advanced square, 15mm, 24 bolts, 288 elements | 51.36 |

Table 5 shows that only the D-advanced structure with the square bolt pattern, 24 bolts, and 288 elements accomplishes the required fundamental frequency. The other structures all failed and have to be modified. Either the bottom can be made thicker or some reinforcements can be added to the

structure.  To keep the structures simple, the shell thickness of the bottom is increased an additional 5mm.

**Table 6: Fundamental Frequencies of modified structures**

| | Mode 1 [Hz] |
|---|---|
| Box-structure round, 20mm, 24 bolts, 216 elements | 26.9 |
| Box-structure square, 25mm, 24 bolts, 288 elements | 48.42 |
| D-advanced round, 20mm, 24 bolts, 216 elements | 46.25 |

The increased shell thickness at the bottom has created the desired results, except for the box-structure which shows a fundamental frequency of 26.9 Hz.  Because of a 5 mm thicker shell, the frequency increased only by 6 Hz and is still under the required 35 Hz.  The other two structures now have acceptable frequencies of 48.42 Hz and 46.25 Hz.

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# IV. CONCLUSION

Two structural designs are possible for an NPSCuL structure, the box-structure and the D-advanced structure. Both fulfill the ESPA requirements and the general requirements of a secondary payload.

The stress analyses which were created with different FE-models showed, that the initial designs had to be modified. The critical areas are the bottom panel with the bolt pattern, the stress values in this area have to be smaller than the maximum allowed stress of the material. That is why the shell thickness was raised until the structures met the structural and dynamics requirements. A thicker shell results in different mass as calculated in III.C.4.

The fundamental frequencies of the different design options calculated in III.D were partly under the required 35 Hz. That is why the shell thickness was raised until the structures had higher frequencies. This also resulted in a higher structural mass.

**Table 7: Modified mass of the structures**

| | Mass [kg] | Remainder [kg] |
|---|---|---|
| Box-structure 10 mm shell | 51.71 | 31 |
| Box-structure 25 mm shell | 63.93 | 18.8 |
| D-advanced 10 mm shell | 31.28 | 51.4 |
| D-advanced 15 mm shell (square) | 33.37 | 49.3 |
| D-advanced 20 mm shell (round) | 35.46 | 47.2 |

Table 7 shows the modified masses of the design options. They still fall below the maximum acceptable mass of 181 kg.

Future research will have to clarify which property is more important, either the capability to carry a 2U by 2U CubeSat or the flexibility gained by a larger mass margin. Therefore, the following structures are under consideration:

a). Box-structure with square bolt pattern, 25 mm bottom shell thickness

b). D-advanced structure with square bolt pattern, 15 mm bottom shell thickness

Option a) is the only possible box-structure. The structural option with a circular bolt pattern and a 15 mm shell thickness accomplishes the required stress values, but the fundamental frequency is too low. To fix this problem, the shell thickness would become too large with an associated increase of mass.

Option b) has nearly the same stress values as the D-advanced structure with the round bolt pattern. However, the results of the fundamental frequencies showed that this option had a considerable higher frequency than the required 35 Hz and no modification was necessary.

# APPENDIX A. MATERIAL PROPERTIES OF AL 7075-T6

Interactive Table - Design Properties    Interactive Table - Typical Properties

**Table 3.7.6.0(b₁). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Sheet and Plate**

| Specification | AMS 4045 and AMS-QQ-A-250/12 | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Form | Sheet | | | | | | | Plate | | | | | | | | | | | | | |
| Temper | T6 and T62[a] | | | | | | | T651 | | | | | | | | | | | | | |
| Thickness, in. | 0.008-0.011 | 0.012-0.039 | | 0.040-0.125 | | 0.126-0.249 | | 0.250-0.499 | | 0.500-1.000 | | 1.001-2.000 | | 2.001-2.500 | | 2.501-3.000 | | 3.001-3.500 | | 3.501-4.000 | |
| Basis | S | A | B | A | B | A | B | A | B | A | B | A | B | A | B | A | B | A | B | A | B |
| Mechanical Properties: | | | | | | | | | | | | | | | | | | | | | |
| $F_{tu}$, ksi: | | | | | | | | | | | | | | | | | | | | | |
| L | ... | 76 | 78 | 78 | 80 | 78 | 80 | 77 | 79 | 77 | 79 | 76 | 78 | 75 | 77 | 71 | 73 | 70 | 72 | 66 | 68 |
| LT | 74 | 76 | 78 | 78 | 80 | 78 | 80 | 78 | 80 | 78 | 80 | 77 | 79 | 76 | 78 | 72 | 74 | 71 | 73 | 67 | 69 |
| ST | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 70[b] | 71[b] | 66[b] | 68[b] | 65[b] | 67[b] | 61[b] | 63[b] |
| $F_{ty}$, ksi: | | | | | | | | | | | | | | | | | | | | | |
| L | ... | 69 | 72 | 70 | 72 | 71 | 73 | 69 | 71 | 70 | 72 | 69 | 71 | 66 | 68 | 63 | 65 | 60 | 62 | 56 | 58 |
| LT | 63 | 67 | 70 | 68 | 70 | 69 | 71 | 67 | 69 | 68 | 70 | 67 | 69 | 64 | 66 | 61 | 63 | 58 | 60 | 54 | 56 |
| ST | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 59[b] | 61[b] | 56[b] | 58[b] | 54[b] | 55[b] | 50[b] | 52[b] |
| $F_{cy}$, ksi: | | | | | | | | | | | | | | | | | | | | | |
| L | ... | 68 | 71 | 69 | 71 | 70 | 72 | 67 | 69 | 68 | 70 | 66 | 68 | 62 | 64 | 58 | 60 | 55 | 57 | 51 | 52 |
| LT | ... | 71 | 74 | 72 | 74 | 73 | 75 | 71 | 73 | 72 | 74 | 71 | 73 | 68 | 70 | 65 | 67 | 61 | 64 | 57 | 59 |
| ST | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 67 | 70 | 64 | 66 | 61 | 63 | 57 | 59 |
| $F_{su}$, ksi | ... | 46 | 47 | 47 | 48 | 47 | 48 | 43 | 44 | 44 | 45 | 44 | 45 | 44 | 45 | 42 | 43 | 42 | 43 | 39 | 41 |
| $F_{bru}$[c], ksi: | | | | | | | | | | | | | | | | | | | | | |
| (e/D = 1.5) | ... | 118 | 121 | 121 | 124 | 121 | 124 | 117 | 120 | 117 | 120 | 116 | 119 | 114 | 117 | 108 | 111 | 107 | 110 | 101 | 104 |
| (e/D = 2.0) | ... | 152 | 156 | 156 | 160 | 156 | 160 | 145 | 148 | 145 | 148 | 143 | 147 | 141 | 145 | 134 | 137 | 132 | 135 | 124 | 128 |
| $F_{bry}$[c], ksi: | | | | | | | | | | | | | | | | | | | | | |
| (e/D = 1.5) | ... | 100 | 105 | 102 | 105 | 103 | 106 | 97 | 100 | 100 | 103 | 100 | 103 | 98 | 101 | 94 | 97 | 89 | 93 | 84 | 87 |
| (e/D = 2.0) | ... | 117 | 122 | 119 | 122 | 121 | 124 | 114 | 118 | 117 | 120 | 117 | 120 | 113 | 117 | 109 | 112 | 104 | 108 | 98 | 103 |
| $e$, percent (S-basis): | | | | | | | | | | | | | | | | | | | | | |
| LT | 5 | 7 | ... | 8 | ... | 8 | ... | 9 | ... | 7 | ... | 6 | ... | 5 | ... | 5 | ... | 5 | ... | 3 | ... |
| $E$, $10^3$ ksi | 10.3 | | | | | | | 10.3 | | | | | | | | | | | | | |
| $E_c$, $10^3$ ksi | 10.5 | | | | | | | 10.6 | | | | | | | | | | | | | |
| $G$, $10^3$ ksi | 3.9 | | | | | | | 3.9 | | | | | | | | | | | | | |
| $\mu$ | 0.33 | | | | | | | 0.33 | | | | | | | | | | | | | |
| Physical Properties: | | | | | | | | | | | | | | | | | | | | | |
| $\omega$, lb/in.$^3$ | 0.101 | | | | | | | | | | | | | | | | | | | | |
| $C$, $K$, and $\alpha$ | See Figure 3.7.6.0 | | | | | | | | | | | | | | | | | | | | |

a Design allowables were based upon data obtained from testing T6 temper sheet and from testing samples of sheet, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.

b Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

c Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

## APPENDIX B. FORCES OF THE SIMPLE FE-MODEL

| | |
|---|---|
| Acceleration [g] | 10.00 |
| | |
| Mass 3U P-PODs [kg] | 5.25 |
| Mass 5U P-PODs [kg] | 8.09 |
| | |
| absolut force 3U [N] | 5150.25 |
| absolut force 5U [N] | 7936.29 |
| | |
| 3U force per node (10) [N] | 515.03 |
| 3U force per node (60) [N] | 85.84 |
| | |
| 5U force per node (10) [N] | 793.63 |
| 5U force per node (60) [N] | 132.27 |

## APPENDIX C. MASS CONFIGURATIONS

| | H open | H wrapped | H fully enclosed | box wrapped | box fully enclosed |
|---|---|---|---|---|---|
| | | | | | |
| description | H-structure | H-structure covered by an outer box | H-structure covered by an outer box with a lid on top | the box-structure is supporting and covering structure at the same time | wrapepd box enclosed by a lid |
| | | | | | |
| **max ESPA payload [kg]** | **181.00** | **181.00** | **181.00** | **181.00** | **181.00** |
| | | | | | |
| 10 P-PODs [kg] | 80.90 | 80.90 | 80.90 | 80.90 | 80.90 |
| P-POD (1) | 3.09 | 3.09 | 3.09 | 3.09 | 3.09 |
| Payload (5U) | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 |
| | | | | | |
| NPSCuL [kg] | 34.00 | 34.00 | 34.00 | 58.89 | 58.89 |
| P-POD support structure | 26.82 | 26.82 | 26.82 | 51.71 | 51.71 |
| base plate | 7.18 | 7.18 | 7.18 | 7.18 | 7.18 |
| | | | | | |
| outer box (5 sides) [kg] | - | 29.34 | 29.34 | - | - |
| lid [kg] | - | - | 3.16 | - | 3.16 |
| | | | | | |
| lightband (if deployable) [kg] | 2.54 | 2.54 | 2.54 | 2.54 | 2.54 |
| | | | | | |
| Electronics (estimate) [kg] | 7.00 | 7.00 | 7.00 | 7.00 | 7.00 |
| wires & connectors | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| batteries | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 |
| circuit board + box | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | | | | | |
| Screws [kg] | 0.79 | 0.58 | 0.58 | 0.68 | 0.68 |
| screw (P-Pod to structure) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| screw (structure to base plate) | 0.01 | - | - | 0.01 | 0.01 |
| screw (structure to base plate thru outer box) | - | 0.01 | 0.01 | - | - |
| counter sink (structure itself) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| screw base to light band | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| | | | | | |
| total mass [kg] | **125.2** | **154.4** | **157.5** | **150.0** | **153.2** |
| remainder to max ESPA payload [kg] | **55.8** | **26.6** | **23.5** | **31.0** | **27.8** |

| | D open | D wrapped | D fully enclosed |
|---|---|---|---|
| | | | |
| description | D-structure | D-structure wrapped by an outer box | D-structure enclosed by an outer box with a lid on top |
| | | | |
| **max ESPA payload [kg]** | **181.00** | **181.00** | **181.00** |
| | | | |
| 10 P-PODs [kg] | 80.90 | 80.90 | 80.90 |
| P-POD (1) | 3.09 | 3.09 | 3.09 |
| Payload (5U) | 5.00 | 5.00 | 5.00 |
| | | | |
| NPSCuL [kg] | 36.52 | 36.52 | 36.52 |
| P-POD support structure | 29.34 | 29.34 | 29.34 |
| base plate | 7.18 | 7.18 | 7.18 |
| | | | |
| outer box (5 sides) [kg] | - | 29.34 | 29.34 |
| lid [kg] | - | - | 3.16 |
| | | | |
| lightband (if deployable) [kg] | 2.54 | 2.54 | 2.54 |
| | | | |
| Electronics (estimate) [kg] | 7.00 | 7.00 | 7.00 |
| wires & connectors | 1.00 | 1.00 | 1.00 |
| batteries | 5.00 | 5.00 | 5.00 |
| circuit board + box | 1.00 | 1.00 | 1.00 |
| | | | |
| Screws [kg] | 0.68 | 0.58 | 0.00 |
| screw (P-Pod to structure) | 0.01 | 0.01 | 0.00 |
| screw (structure to base plate) | 0.01 | - | - |
| screw (structure to base plate thru outer box) | - | 0.01 | 0.00 |
| counter sink (structure itself) | 0.01 | 0.01 | 0.00 |
| screw base to light band | 0.01 | 0.01 | 0.00 |
| | | | |
| total mass [kg] | **127.6** | **156.9** | **159.5** |
| remainder to max ESPA payload [kg] | **53.4** | **24.1** | **21.5** |

## APPENDIX D. MODIFIED MASS CONFIGURATIONS

| | box wrapped | box fully enclosed |
|---|---|---|
| | | |
| description | the box-structure is supporting and covering structure at the same time | wrapepd box enclosed by a lid |
| shell thickness | 25 mm | 25 mm |
| | | |
| **max ESPA payload [kg]** | **181.00** | **181.00** |
| | | |
| 10 P-PODs [kg] | 80.90 | 80.90 |
| P-POD (1) | 3.09 | 3.09 |
| Payload (5U) | 5.00 | 5.00 |
| | | |
| NPSCuL [kg] | 71.11 | 71.11 |
| P-POD support structure | 63.93 | 63.93 |
| base plate | 7.18 | 7.18 |
| | | |
| outer box (5 sides) [kg] | - | - |
| lid [kg] | - | 3.16 |
| | | |
| lightband (if deployable) [kg] | 2.54 | 3.54 |
| | | |
| Electronics (estimate) [kg] | 7.00 | 7.00 |
| wires & connectors | 1.00 | 1.00 |
| batteries | 5.00 | 5.00 |
| circuit board + box | 1.00 | 1.00 |
| | | |
| Screws [kg] | 0.68 | 0.68 |
| screw (P-Pod to structure) | 0.01 | 0.01 |
| screw (structure to base plate) | 0.01 | 0.01 |
| screw (structure to base plate thru outer box) | - | - |
| counter sink (structure itself) | 0.01 | 0.01 |
| screw base to light band | 0.01 | 0.01 |
| | | |
| total mass [kg] | **162.2** | **166.4** |
| remainder to max ESPA payload [kg] | **18.8** | **14.6** |

| | D-advanced open | D-advanced wrapped | D-advanced fully enclosed | D-advanced open | D-advanced wrapped | D-advanced fully enclosed |
|---|---|---|---|---|---|---|
| | | | | | | |
| description | D-structure | D-structure wrapped by an outer box | D-structure enclosed by an outer box with a lid on | D-structure | D-structure wrapped by an outer box | D-structure enclosed by an outer box with a lid on |
| shell thickness | 15 mm | 15 mm | 15 mm | 20 mm | 20 mm | 20 mm |
| | | | | | | |
| **max ESPA payload [kg]** | **181.00** | **181.00** | **181.00** | **181.00** | **181.00** | **181.00** |
| | | | | | | |
| 10 P-PODs [kg] | 80.90 | 80.90 | 80.90 | 80.90 | 80.90 | 80.90 |
| P-POD (1) | 3.09 | 3.09 | 3.09 | 3.09 | 3.09 | 3.09 |
| Payload (5U) | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 |
| | | | | | | |
| NPSCuL [kg] | 40.55 | 40.55 | 40.55 | 42.64 | 42.64 | 42.64 |
| P-POD support structure | 33.37 | 33.37 | 33.37 | 35.46 | 35.46 | 35.46 |
| base plate | 7.18 | 7.18 | 7.18 | 7.18 | 7.18 | 7.18 |
| | | | | | | |
| outer box (5 sides) [kg] | - | 29.34 | 29.34 | - | 29.34 | 29.34 |
| lid [kg] | - | - | 3.16 | - | - | 3.16 |
| | | | | | | |
| lightband (if deployable) [kg] | 2.54 | 2.54 | 2.54 | 2.54 | 2.54 | 2.54 |
| | | | | | | |
| Electronics (estimate) [kg] | 7.00 | 7.00 | 7.00 | 7.00 | 7.00 | 7.00 |
| wires & connectors | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| batteries | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 |
| circuit board + box | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | | | | | | |
| Screws [kg] | 0.68 | 0.58 | 0.00 | 0.68 | 0.58 | 0.00 |
| screw (P-Pod to structure) | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.00 |
| screw (structure to base plate) | 0.01 | - | - | 0.01 | - | - |
| screw (structure to base plate thru outer box) | - | 0.01 | 0.00 | - | 0.01 | 0.00 |
| counter sink (structure itself) | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.00 |
| screw base to light band | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.00 |
| | | | | | | |
| total mass [kg] | **131.7** | **160.9** | **163.5** | **133.8** | **163.0** | **165.6** |
| remainder to max ESPA payload [kg] | **49.3** | **20.1** | **17.5** | **47.2** | **18.0** | **15.4** |

# APPENDIX E. RESULTS OF THE FE-MODELS

**D-round (24 bolts)** element length: 1.983 cm **shell thickness: 10mm** max: 4.82*10^8

| elements on circle | number of elements | min. displacement | max. displacement | max. stress [10^8] |
|---|---|---|---|---|
| | | | | |
| 24 | | -0.00708 | 0.00666 | 3.28 |
| 48 | | -0.00707 | 0.00665 | 3.9 |
| 96 | | -0.00707 | 0.00665 | 4.51 |
| 120 | | -0.00707 | 0.00665 | 4.66 |
| 144 | | -0.00708 | 0.00665 | 4.75 |
| 192 | | -0.00708 | 0.00666 | 5 |
| 216 | | -0.00708 | 0.00666 | 5.13 |

**D-round (24 bolts)** element length: 1.983 cm **shell thickness: 15mm** max: 4.82*10^8

| elements on circle | number of elements | min. displacement | max. displacement | max. stress [10^8] |
|---|---|---|---|---|
| | | | | |
| 24 | | -0.00263 | 0.00243 | 1.67 |
| 48 | | -0.00263 | 0.00243 | 1.93 |
| 72 | | -0.00264 | 0.00244 | 2.13 |
| 96 | | -0.00264 | 0.00244 | 2.16 |
| 120 | | -0.00264 | 0.00244 | 2.21 |
| 144 | | -0.00265 | 0.00244 | 2.27 |
| 192 | | -0.00265 | 0.00245 | 2.35 |
| 216 | | -0.00265 | 0.00245 | 2.41 |

**D-square (16 bolts)** element length: 1.983 cm **shell thickness: 10mm** max: 4.82*10^8

| elements on edge | number of elements | min. displacement | max. displacement | max. stress [10^8] |
|---|---|---|---|---|
| | | | | |
| 16 | 64 | -0.0029 | 0.00255 | 3.7 |
| 32 | 128 | -0.0029 | 0.00255 | 4.84 |
| 48 | 172 | -0.00293 | 0.00257 | 5.7 |

**D-square (20 bolts)** element length: 1.983 cm **shell thickness: 10mm** max: 4.82*10^8

| elements on edge | number of elements | min. displacement | max. displacement | max. stress [10^8] |
|---|---|---|---|---|
| | | | | |
| 10 | 40 | -0.00265 | 0.00232 | 3.07 |
| 20 | 80 | -0.00265 | 0.00232 | 4.39 |
| 30 | 120 | -0.00265 | 0.00232 | 4.82 |
| 40 | 160 | -0.00266 | 0.00232 | 5.15 |
| 50 | 200 | -0.00266 | 0.00233 | 5.61 |

**D-square (24 bolts)** element length: 1.983 cm **shell thickness: 10mm** max: 4.82*10^8

| elements on edge | number of elements | min. displacement | max. displacement | max. stress [10^8] |
|---|---|---|---|---|
| | | | | |
| 12 | 48 | -0.00249 | 0.00217 | 3.66 |
| 24 | 96 | -0.00248 | 0.00216 | 4.56 |
| 36 | 144 | -0.00276 | 0.00242 | 5.25 |

**D-square (24 bolts)**

element length: 1.983 cm **shell thickness: 15mm** max: 4.82*10^8

| elements on edge | number of elements | min. displacement | max. displacement | max. stress [10^8] |
|---|---|---|---|---|
| | 0 | | | |
| 12 | 48 | -0.00108 | 0.000938 | 1.88 |
| 24 | 96 | -0.00109 | 0.000943 | 2.24 |
| 36 | 144 | -0.0011 | 0.000949 | 2.46 |
| 48 | 192 | -0.0011 | 0.000953 | 2.58 |
| 60 | 240 | -0.00111 | 0.000958 | 2.7 |
| 72 | 288 | -0.00111 | 0.000963 | 2.8 |

**Box-square (20 bolts)** element length: 2.023 cm **shell thickness: 10mm** max: 4.82*10^8

| elements on edge | number of elements | min. displacement | max. displacement | max. stress [10^8] |
|---|---|---|---|---|
| | | | | |
| 10 | 40 | -0.0214 | 0.0158 | 6.78 |
| 20 | 80 | -0.0214 | 0.0158 | 7.89 |

**Box-square (24 bolts)** element length: 2.023 cm **shell thickness: 10mm** max: 4.82*10^8

| elements on edge | number of elements | min. displacement | max. displacement | max. stress [10^8] |
|---|---|---|---|---|
| | | | | |
| 12 | 48 | -0.0208 | 0.0154 | 7.38 |
| 24 | 96 | -0.0208 | 0.0154 | 8.57 |

**Box-square (24 bolts)** element length: 2.023 cm **shell thickness: 20mm** max: 4.82*10^8

| elements on edge | number of elements | min. displacement | max. displacement | max. stress [10^8] |
|---|---|---|---|---|
| | 0 | | | |
| 12 | 48 | -0.00352 | 0.00234 | 1.97 |
| 24 | 96 | -0.00352 | 0.00235 | 2.22 |
| 36 | 144 | -0.00355 | 0.00236 | 2.36 |
| 48 | 192 | -0.00357 | 0.00232 | 2.53 |
| 60 | 240 | -0.00357 | 0.00237 | 2.54 |
| 72 | 288 | -0.00358 | 0.00237 | 2.61 |

**Box-square (24 bolts)** element length: 2.023 cm **shell thickness: 15mm** max: 4.82*10^8

| elements on edge | number of elements | min. displacement | max. displacement | max. stress [10^8] |
|---|---|---|---|---|
| | | | | |
| 12 | 48 | -0.00743 | 0.00517 | 3.45 |
| 24 | 96 | -0.00745 | 0.00518 | 3.94 |
| 36 | 144 | -0.00747 | 0.0052 | 4.23 |
| 48 | 192 | -0.00749 | 0.00521 | 4.45 |
| 60 | 240 | -0.0075 | 0.00522 | 4.58 |
| 72 | 288 | -0.00751 | 0.00522 | 4.73 |

**Box-round (24 bolts)** element length: 2.023 cm **shell thickness: 10mm** max: 4.82*10^8

| elements on circle | number of elements | min. displacement | max. displacement | max. stress [10^8] |
|---|---|---|---|---|
| | | | | |
| 24 | | -0.0228 | 0.0314 | 5.31 |
| 48 | | -0.0228 | 0.0313 | 5.58 |

**Box-round (24 bolts)** element length: 2.023 cm **shell thickness: 15mm** max: 4.82*10^8

| elements on circle | number of elements | min. displacement | max. displacement | max. stress [10^8] |
|---|---|---|---|---|
| | | | | |
| 24 | | -0.00732 | 0.0108 | 2.52 |
| 48 | | -0.00731 | 0.0108 | 2.65 |
| 72 | | -0.00732 | 0.0108 | 2.79 |
| 96 | | -0.00732 | 0.0108 | 2.88 |
| 120 | | -0.00733 | 0.0108 | 2.92 |
| 144 | | -0.00733 | 0.0108 | 2.94 |
| 168 | | -0.00733 | 0.0108 | 2.98 |
| 192 | | -0.00733 | 0.0108 | 3 |
| 216 | | -0.00733 | 0.0108 | 3.05 |

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